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TOWARDS HIGH-REPETITION RATE PETAWATT LASER EXPERIMENTS WITH CRYOGENIC JETS USING A MECHANICAL CHOPPER SYSTEM

M. Rehwald*[1], S. Assenbaum[1], C. Bernert[1], U. Schramm[1], K. Zeil
Helmholtz-Zentrum Dresden - Rossendorf, Institute of Radiation Physics,
Bautzner Landstr. 400, 01328 Dresden, Germany
S. Göde, European XFEL GmbH, Holzkoppel 4, 22869 Schenefeld, Germany
C. B. Curry[2], M. Gauthier, S. H. Glenzer, C. Schoenwaelder[3], F. Treffert[4]
High Energy Density Science Division, SLAC National Accelerator Laboratory, Menlo Park,
California 94025, USA
[1] also at Technische Universität Dresden, 01062 Dresden, Germany
[2] also at University of Alberta, Edmonton, Alberta T6G 1H9, Canada
[3] also at Friedrich-Alexander Universität Erlangen-Nürnberg, 91054 Erlangen, Germany
[4] also at Technische Universität Darmstadt, 64289 Darmstadt, Germany

Abstract

Laser-plasma based ion accelerators require suitable high-repetition rate target systems that enable systematic studies at controlled plasma conditions and application-relevant particle flux. Self-refreshing, micrometer-sized cryogenic jets have proven to be an ideal target platform. Yet, operation of such systems in the harsh environmental conditions of high power laser induced plasma experiments have turned out to be challenging. Here we report on recent experiments deploying a cryogenic hydrogen jet as a source of pure proton beams generated with the PW-class ultrashort pulse laser DRACO. Damage to the jet target system during application of full energy laser shots was prevented by implementation of a mechanical chopper system interrupting the direct line of sight between the laser plasma interaction zone and the jet source.

INTRODUCTION

Laser-driven particle sources have been studied extensively over the last two decades[1]. The interest originates from unique beam properties that are useful for a number of applications ranging from ultrafast electromagnetic field probes [2, 3] and high flux neutron converter for material radiography [4] through isochoric heating of warm dense matter [5] and inertial confinement fusion [6] to injection sources for conventional accelerator structures [7] and medical applications [8–10]. Ongoing research in this field aims for the realization of a sufficiently high repetition rate which is needed to achieve application-relevant particle yields. Therefore target systems are required that are suitable for the challenges arising from the high laser shot rates. This includes target insertion and alignment as well as mitigation of debris produced by the evaporation of the target material during the shot potentially causing coating and damage of sensitive optical components. Recently developed renewable cryogenic jets allow for debris-free operation and rapid injection of fresh targets [11, 12]. No debris is produced as the material is gaseous at ambient temperatures and removed by the vacuum pumps.

The target system has to withstand the harsh environment of the high-power laser plasma interaction. When the laser pulse hits the target, energy is transferred to target electrons which can be accelerated to relativistic energies. This results in broad emission of radiation as the electrons recirculate inside the target and further interact with the laser light. The most energetic electrons are emitted from the target, building up charge separation fields, that lead to the acceleration of ions. The charge imbalance in the interaction region drives return currents in the target assembly, and the radiation pressure from the high intensity laser launches spherical shock waves which have a component along the jet axis. These combined effects of energy dissipation into vacuum (radiation, charged particles) or within the bulk of the target may not only cause problems with electronic systems (motors, diagnostics etc..) but can also damage the jet target system itself (the nozzle aperture in particular).

At laser powers in the 100 TW range, cryogenic hydrogen jet targets were successfully implemented and operated in a number of experiments [13–15]. Damage was mainly prevented by focusing the laser at a sufficient distance from the target source. This comes at the cost of increased shot-to-shot fluctuations due to the pointing jitter of the flowing jet. Extending the scope of applications of laser-driven beams demands higher particle energies that can only be realized with petawatt-class laser systems. This intuitively worsens the potential for damage. Besides further increasing the distance between target source and interaction point which would substantially decrease the hit rate, replacing the damaged part after every shot was the second option until now. Clearly, both options are incompatible with systematic studies with high repetition rates and therefore more advanced methods are needed.

In this paper, we report on implementation and demonstration of two new methods to shield the target system from damage caused by the high-power laser plasma interaction. First, the solid jet between the interaction point and the tar-

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* m.rehwald@hzdr.de

get system is interrupted by the help of a cutting laser pulse synchronized to main driver laser pulse. This prevents the energy transfer in the bulk of the target. The second approach is the use of mechanical cutting with a rotating blade completely blocking the line-of-sight between interaction zone and nozzle. Such chopper systems are an established technology in atomic and molecular gas jets as velocity filters. The increased protection requires temporal synchronization of the blade position. The mechanical cutting technique enabled systematic studies with PW-class laser systems and the jet target. This allows the proton acceleration performance to be evaluated at different experimental settings (e.g. different temporal laser pulse shapes) which benefits from the virtually unlimited number of shots possible with the self-replenishing jet target.

EXPERIMENTAL SETUP

The experimental setup for laser proton acceleration is illustrated in Fig. 1. The Titanium:Sapphire based laser system DRACO[16] is used to deliver linearly polarized pulses with up to 23 J energy on target and a duration of 30 fs yielding peak intensities of about $6.8 \cdot 10^{21}$ W/cm^2 at a focal spot size of 2.6 µm (FWHM). A solid hydrogen jet target [11, 12] was produced by injecting pure liquid hydrogen at a temperature of about 18 K through an aperture of 5 µm diameter into vacuum where evaporative cooling caused solidification. With a velocity of around 100 m/s, the jet is continuously refreshing. Time-resolved high resolution shadowgraphy images were recorded employing an off-harmonic optical probe laser system (515 nm wavelength) [17] to characterize and align the hydrogen jet. Laser-accelerated protons were recorded by a Thomson parabola spectrometer (TPS), implemented in laser forward direction. The TPS was equipped with a microchannel plate (MCP) containing a phosphor screen that was imaged onto a camera for on-line readout.

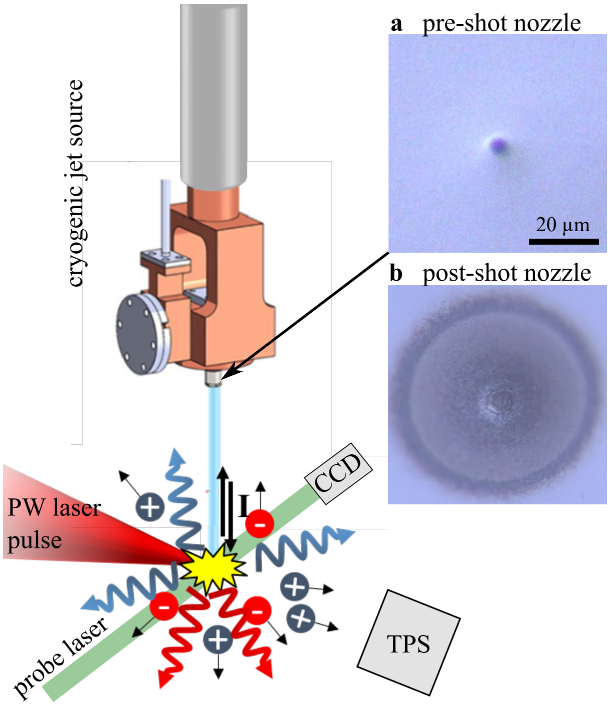

Figure 1: Schematic of the experimental setup: DRACO PW laser pulses (red) are focused onto a cylindrical cryogenic hydrogen jet target (light blue). A synchronized optical probe laser pulse with 515 nm wavelength (green) was used as a backlighter for shadowgraphy imaging. A Thomson parabola spectrometer (TPS) was positioned along the laser propagation direction for proton energy spectra measurement. Strong charged particles and electromagnetic radiation emission as well as laser-driven currents and shocks from the laser-plasma interaction impact the 5 µm nozzle aperture (a) and destroy it in a single laser shot (b).

In the harsh environment of the high-power laser plasma interaction, radiation and charged particle emission as well as the energy transferred along the jet axis can damage the target system (see Fig. 1). The micrometer-sized aperture nozzle is hereby the most fragile part and by that prone to being damaged, as demonstrated by the microscopic images of a nozzle before and after a single laser shot without protection measures in Fig. 1a and b, respectively. The laminar flow of the liquid through the nozzle gets disturbed or even completely blocked and the jet operation stops. As such, only a very limited number of shots would be achievable when using this setup without additional protection. To mitigate the damaging effect, two concepts for shielding the aperture were implemented and tested. While laser cutting only disrupts the solid connection between the interaction point and the sensitive nozzle, mechanical cutting completely blocks the direct line-of-sight.

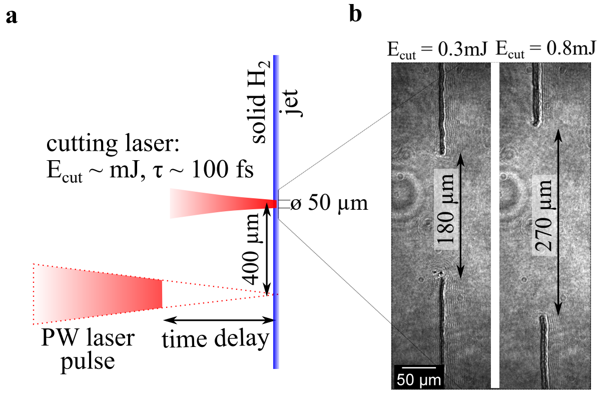

Figure 2: a) Arrangement of the cutting laser beam featuring an energy E_{cut} on the mJ-level, a pulse duration $\tau \approx 100$ fs and a focal spot size of 50 µm. The cutting beam hits the jet target 400 µm above the focus position of the high-intensity laser with a time offset of several tens of nanoseconds. Optical probing images (b) indicate a few 100 µm wide gap in the solid jet 10 ns after the irradiation with the cutting pulse.

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Laser Cutting

A cutting laser beam is introduced into the experimental setup (Fig. 2a) to study if interruption of the cryogenic jet can prevent damaging of the nozzle. The cutting pulse was generated from a portion of the high-intensity beam and focused to a spot size of 50 µm. Irradiation with pulse energies E_{cut} of at least 0.3 mJ is sufficient for ionizing the solid hydrogen as the peak intensity of the laser pulse is estimated to be in the order of 10^{14} to 10^{15} W/cm^2 (depending on E_{cut}) and thus larger than the barrier-suppression ionization threshold for hydrogen atoms (1.37×10^{14} W/cm^2) [18]. After a duration of 10 ns the solid hydrogen is completely vaporized on 180 µm length (see left image in Fig. 2b) and a gap in the jet is formed which represents the introduced interruption. This duration is sufficiently short with respect to the delay of several tens of nanoseconds between cutting and high-intensity laser pulse. Intuitively, an increase in pulse energy to $E_{cut} = 0.8$ mJ (right image in Fig. 2b) leads to a larger gap size as the ionization threshold intensity is exceeded within a larger area. It is important to note that the laser cutting does not result in any observable modifications of the solid jet in the region where the interaction of the high-intensity laser takes place with the target at about 0.4 mm below the cutting region.

However, the application of laser cutting during high-power shots resulted in little improvement only as the jet did not stop immediately but became unstable due to accumulating damage to the aperture. The energy emitted by radiation and charged particles (traveling across the vacuum gap) is therefore assumed to be the main cause of nozzle damage and needs to be shielded mechanically. As a positive outcome for future studies, laser cutting enables precise and stable generation of gaps in the target, jet snippets which may be of particular interest for investigating mass limited targets [19].

Mechanical Chopper

A second approach to mitigate the aperture damage is to utilize a mechanical cutting device, referred to as *mechanical chopper*, that intercepts the energy transfer along the jet and blocks the line-of-sight. Crucial for the error-free operation is a precise synchronization of the blade position in time and space with respect to the laser pulse arrival. The upper limit for the temporal synchronization is defined by the duration that the jet needs to travel the distance between the nozzle and the interaction point. For a typical distance of 10 mm and a flow velocity of $\approx$ 100 m/s, a precision better than 100 µs is required. A more accurate synchronization, of course, allows for a smaller distance to the nozzle and thus improved target stability.

For the implementation in the experiment, a fast spinning blade is used, which is inserted between the aperture and the interaction point and which is driven by a direct current electric motor. The blade is made of few millimeters long, diamond-shaped metal pins (1 mm in size) on the outer edges of a center section made of plastic to isolate the motor from return currents. The rotation of the electric motor is synchronized to a 10 Hz laser trigger signal by a phase-locked loop motor speed controller (based on *Thorlabs MC2000B-EC*) as illustrated in Fig. 3a. The blade rotates with a much higher frequency, typically 75 Hz, to increase the relative phase stability. The actual blade rotation is further detected by a light sensor consisting of a laser diode and a photodiode. The light sensor provides feedback to the controller allowing to adjust the rotation speed with respect to the trigger signal.

The on-shot position of the blade is measured and adjusted using a low magnification imaging system using the probe laser to achieve the cutting synchronized to the irradiation with the high-intensity laser pulse. The recorded image in Fig. 3b illustrates the situation where the cut edge is positioned about 2 mm above the interaction point. Momentum transfer from the blade causes a small curl at the edge of the jet resulting in a deflection of the target within the first 0.5 mm below the cutting point. However, the jet stability is not affected at greater distances. A study of the temporal stability of the mechanical cutting is shown in Fig. 3c. The blue data points indicate the position of the edge of the cut (see probe image in Fig. 3b) for 90 consecutive images at 1 Hz. The stability of the edge position can be characterized by a standard deviation of 0.6 mm while 1.6 mm marks the highest offset from the average.

The implementation of the mechanical chopper in the laser-plasma experiment showed that damage to the aperture was successfully prevented by cutting the jet and blocking the line-of-sight. This enabled systematic studies of laser proton acceleration at the petawatt level.

LASER PROTON ACCELERATION RESULTS

During a measurement campaign of several days, more than 1000 high-intensity laser shots were focused onto the cryogenic jet without damaging the aperture demonstrating the success of the chopper concept. Broadband proton beams were accelerated with large divergence from the plasma similar to what was published in [13] for lower laser pulse energies. Cut-off energies of proton energy spectra measured along the laser main axis being characteristic for the accelerator performance are given in Fig. 4 for one day of operation. Consecutive shots applied at different laser pulse energies on target are shown. Starting at low values, the laser pulse energy was slowly increased while monitoring for potential damage to the target system. No degradation could be detected with respect to the maximum proton energies as shown by the consistent trend of the data points in Fig. 4. Protons with a kinetic energy above 4 MeV, the lower detection threshold of the TPS, were detected in at least 90% of the shots. The large shot-to-shot fluctuation is caused by the non-perfect spatial overlap of the laser focus spot and the target that can be independently monitored using the optical shadowgraphy images. While best performance is obtained for perfect hits, larger lateral distance to the jet axis is in general yielding lower maximum proton energies.

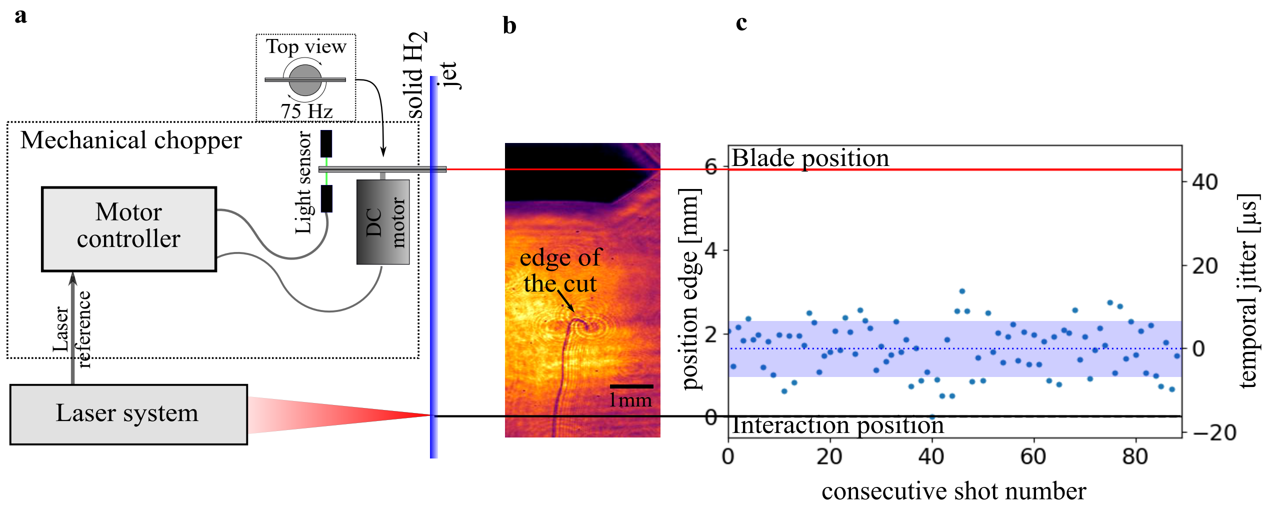

Figure 3: a) Schematic drawing of the components of the mechanical chopper (DC motor with a rotating blade, a light barrier, a motor controller and a laser reference signal). b) A shadowgraphy image generated by back-illumination with the optical probe beam, that is synchronized to the high-intensity laser, shows the chopper blade (black bar in the top of the image), the cryogenic jet in the bottom of the image and the cutting edge. The chopper blade is located 4 mm below the nozzle. c) Characterization of the stability of the mechanical chopper. Red and black horizontal lines illustrate the position of the blade as well as the interaction point. Blue dots indicate the position of the jet edge obtained from probe images for 90 consecutive images at 1 Hz. The blue shaded area illustrates the standard deviation interval.

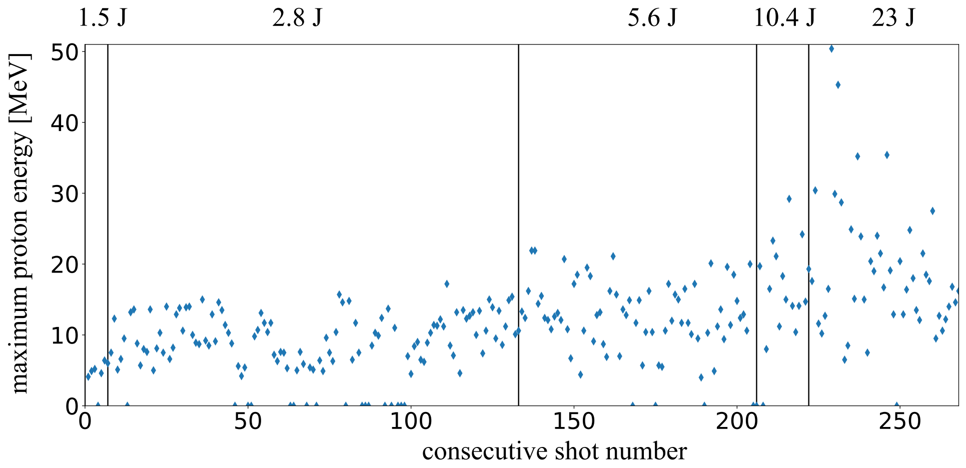

Figure 4: Maximum proton energies measured in laser forward direction for a total of 268 consecutive shots of a single experiment day using different pulse energies on target (displayed at the top). The very same nozzle was used without observing any noticeable performance degradation during the following days of the experiment.

CONCLUSION AND OUTLOOK

We demonstrated laser proton acceleration using an ultrashort pulse PW-class laser systems with a self-refreshing, debris-free cryogenic hydrogen jet target. Recording of a large number of shots was enabled through the implementation of a chopper device that effectively protects the target system from damage due to radiation generated in the laser-plasma interaction. It allowed for systematic studies of proton and ion acceleration regimes in a variety of experimental configurations (to be published elsewhere [20]). It should be noted that such chopper concepts could also be of interest for other target systems where small sensitive nozzles are applied to produce solid or liquid targets for high-power laser experiments [15, 21–23].

In order to further increase the shot-to-shot stability in the experiment, an improved chopper assembly is under development utilizing e.g. a high precision position feedback. The new system guarantee a strongly decreased timing jitter of the rotating blade in the order of few microseconds and will therefore allow to operate the laser plasma interaction even closer to the nozzle. Besides the improved synchronization, the goal is to design a compact assembly to minimize the footprint around the target interaction point.

As an interesting alternative beyond the rotating device, compact piezo driven chopper systems are under consideration. The smaller form factor of piezo designs and much simpler synchronization to the laser pulse arrival time may allow for more flexible on-demand operation schemes.

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REFERENCES

[1] F. Albert *et al.*, “2020 roadmap on plasma accelerators,” *New Journal of Physics*, vol. 23, no. 3, p. 031 101, 2021, doi:10.1088/1367-2630/abcc62

[2] M. Borghesi *et al.*, “Electric field detection in laser-plasma interaction experiments via the proton imaging technique,” *Physics of Plasmas*, vol. 9, no. 5, pp. 2214–2220, 2002, doi:10.1063/1.1459457

[3] K. Quinn *et al.*, “Laser-driven ultrafast field propagation on solid surfaces,” *Physical Review Letters*, vol. 102, pp. 3–6, 2009, doi:10.1103/PhysRevLett.102.194801

[4] M. Roth *et al.*, “Bright laser-driven neutron source based on the relativistic transparency of solids,” *Physical Review Letters*, vol. 110, no. 4, p. 44 802, 2013, doi:10.1103/PhysRevLett.110.044802

[5] P. Patel *et al.*, “Isochoric heating of solid-density matter with an ultrafast proton beam,” *Physical Review Letters*, vol. 91, no. 12, p. 125 004, 2003, doi:10.1103/PhysRevLett.91.125004

[6] J. C. Fernández *et al.*, “Progress and prospects of ion-driven fast ignition,” *Nuclear Fusion*, vol. 49, no. 6, p. 065 004, 2009, doi:10.1088/0029-5515/49/6/065004

[7] S. Busold *et al.*, “Shaping laser accelerated ions for future applications - The LIGHT collaboration,” *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 740, pp. 94–98, 2014, doi:10.1016/j.nima.2013.10.025

[8] S. V. Bulanov, T. Z. Esirkepov, V. S. Khoroshkov, A. V. Kuznetsov, and F. Pegoraro, “Oncological hadrontherapy with laser ion accelerators,” *Physics Letters A*, vol. 299, no. 2-3, pp. 240–247, 2002, doi:10.1016/S0375-9601(02)00521-2

[9] F. Kroll *et al.*, “Tumour irradiation in mice with a laser-accelerated proton beam,” *Nature Physics*, vol. 18, pp. 316–322, 2022, doi:10.1038/s41567-022-01520-3

[10] A. Yogo *et al.*, “Application of laser-accelerated protons to the demonstration of DNA double-strand breaks in human cancer cells,” *Applied Physics Letters*, vol. 94, no. 18, p. 181 502, 2009.

[11] J. B. Kim, S. Göde, and S. H. Glenzer, “Development of a cryogenic hydrogen microjet for high-intensity, high-repetition rate experiments,” *Review of Scientific Instruments*, vol. 87, no. 11, 11E328, 2016, doi:10.1063/1.4961089

[12] C. B. Curry *et al.*, “Cryogenic liquid jets for high repetition rate discovery science,” *Journal of Visualized Experiments*, no. 159, e61130, 2020, doi:10.3791/61130

[13] L. Obst *et al.*, “Efficient laser-driven proton acceleration from cylindrical and planar cryogenic hydrogen jets,” *Scientific Reports*, vol. 7, no. June, p. 10 248, 2017, doi:10.1038/s41598-017-10589-3

[14] M. Gauthier *et al.*, “High repetition rate, multi-MeV proton source from cryogenic hydrogen jets,” *Applied Physics Letters*, vol. 111, no. 11, p. 114 102, 2017, doi:10.1063/1.4990487

[15] J. Polz *et al.*, “Efficient laser-driven proton acceleration from a cryogenic solid hydrogen target,” *Scientific reports*, vol. 9, no. 1, p. 16 534, 2019, doi:10.1038/s41598-019-52919-7

[16] T. Ziegler *et al.*, “Proton beam quality enhancement by spectral phase control of a PW-class laser system,” *Scientific Reports*, vol. 11, no. 1, p. 7338, 2021, doi:10.1038/s41598-021-86547-x

[17] C. Bernert *et al.*, “Off-harmonic optical probing of high intensity laser plasma expansion dynamics in solid density hydrogen jets,” *Scientific Reports*, vol. 12, no. 1, pp. 1–11, 2022, doi:10.1038/s41598-022-10797-6

[18] M. Protopapas, C. H. Keitel, and P. L. Knight, “Atomic physics with super-high intensity lasers,” *Reports on Progress in Physics*, vol. 60, no. 4, pp. 389–486, 1997, doi:10.1088/0034-4885/60/4/001

[19] S. Buffechoux *et al.*, “Hot electrons transverse refluxing in ultraintense laser-solid interactions,” *Physical Review Letters*, vol. 105, p. 015 005, 2010, doi:10.1103/PhysRevLett.105.015005

[20] M. Rehwald *et al.*, “Ultra-short pulse laser acceleration of protons to 80 MeV from cryogenic hydrogen jets tailored to near-critical density,” submitted for publication.

[21] J. D. Koralek *et al.*, “Generation and characterization of ultrathin free-flowing liquid sheets,” *Nature Communications*, vol. 9, no. 1, p. 1353, 2018, doi:10.1038/s41467-018-03696-w

[22] K. M. George *et al.*, “High-repetition-rate (kHz) targets and optics from liquid microjets for high-intensity laser–plasma interactions,” *High Power Laser Science and Engineering*, vol. 7, e50, 2019, doi:10.1017/hpl.2019.35

[23] S. Garcia, D. Chatain, and J. P. Perin, “Continuous production of a thin ribbon of solid hydrogen,” *Laser and Particle Beams*, vol. 32, no. 4, pp. 569–575, 2014, doi:10.1017/S0263034614000524