Final report on DOE Grant DE-FG02-07ER41488-A002
High-brightness picosecond ion beam source based on BNL Terawatt
CO₂ laser: Proof-of-principle experiments

Peter Shkolnikov, Ph. D., Principal Investigator

Summary

This report covers our pioneering research, under DOE support, on proton and ion generation in gas jets by the world's first picosecond TW CO₂ laser, with the detailed description of the most recent research done under this grant.

Our initial proposal set the goal of building and studying a high-brightness multi-MeV ion and proton beam source driven by a pioneering BNL picosecond Terawatt (TW) CO₂ laser, ions and protons to be accelerated eventually to multi-MeV energies in the interaction of that laser's radiation with metal foils and gas jets. When we began this research, laser-ion acceleration experiments were conducted exclusively with solid-state lasers at $\lambda \sim < 1 \text{ } \mu\text{m}$, simply because only those lasers were capable of generating ultrashort TW pulses. We expect mid-IR ($\lambda \sim 10 \text{ } \mu\text{m}$) lasers to be significantly more efficient in driving ion acceleration in laser plasma. Moreover, our experiments are conducted in the area of laser-plasma parameters that remained almost unexplored until recently. Better understanding of plasma physics in the relativistic ultrashort mid-IR laser fields will certainly contribute to other applications as well, such as ICF.

Under the continuing DOE support, we have:

- assembled the basic experiment setup and then continued expanding it to include diverse diagnostics and to accommodate gas jet targets in addition to metal foils;
- conducted an extensive study of our novel laser, significantly enhanced laser beam diagnostics, and improved relevant laser parameters;
- turned our experiments into a truly international endeavor with active collaboration of close to 20 researchers in US, UK, and Germany;

- conducted the first ever experiments with proton and ion acceleration by lasers interacting with overcritical plasma of gas jets;
- for the first time directly observed radiation pressure acceleration of protons, including quasi-monoenergetic spectra promising for future applications;
- for the first time directly observed quasi-stable, bubble-like plasma structures that likely evolved from relativistic laser-plasma solitons (post-solitons).

Thus, we have confirmed a strong potential of a picosecond TW CO₂ laser as a research tool in laser-plasma science and as a promising vehicle for future applications of laser ion acceleration. This has led to apparent increase of the interest in mid-IR laser ion acceleration. In particular, another major research group began extensive proton acceleration experiments with their own CO₂ laser at UCLA. As a result, the mechanisms responsible for laser proton acceleration in gas jets have become somewhat clearer. It is also important to note that modest DOE funding played the role of a seed support ensuring the formation of a multinational research team, whose members contributed its time and equipment with value well in excess of that seed amount.

Project Research Team

Our project has become a multinational effort. The following is the list of current and past members of our team, which includes 9 institutions from three countries:

USA

*Stony Brook University: **Peter Shkolnikov, PI, Theory; Michael Ispiryan** (since left) and **Chakra Mahajan** (hired under the new DOE grant), **Experiment***

*ATF BNL: **Igor Pogorelsky (Head of experiments), Vitaly Yakimenko, Marcus Babzien, Michael Polyansky, and Oliver Tresca** **Experiment***

*Columbia Univ., New York: **Elena Stolyarova, George Flynn, Experiment***

*University of M College Park: **Galina Dudnikova, Computer simulations***

UK

*University of Strathclyde, Glasgow: **Paul McKenna, David Carroll, Experiment***

*Rutherford Appleton Lab, Central Laser Facility, Oxford: **David Neely, Experiment***

*The Blackett Laboratory, Imperial College, London: **C. A. J. Palmer, N. P., Dover, A. E. Dangor, and Z. Najmudin, Experiment and computer simulations***

Germany

*Heinrich-Heine-Universitat Dusseldorf: **Min Chen, Alexander Pukhov, Theory***

*Max-Planck-Institut fur Quantenoptik: **J. J. Schreiber, Theory***

All international participants have provided their time and rental of important, sometimes unique equipment *pro bono*.

Relevant publications of our group

Refereed Journal Articles

1. I. V. Pogorelsky, M. N. Polyanskiy, M. Babzien, V. Yakimenko, N. P. Dover, C. A. J. Palmer, Z. Najmudin, P. Shkolnikov, G. Dudnikova, *Laser Induced Cavities and Solitons in Overcritical Hydrogen Plasma*, Laser Physics **21**, 1288-1294 (2011)
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3. Z. Najmudin, C. Palmer, N. Dover, I. Pogorelsky, M. Babzien, A. E. Dangor, G. I. Dudnikova, P. S. Foster, J. S. Green, M. Ispiryan, D. Neely, M. Polyanskiy, J. Schreiber, P. Shkolnikov and V. Yakimenko, *Observation of impurity free monoenergetic proton beams from the interaction of a CO₂ laser with a gaseous target*, Phys. Plasmas **18**, 056705 (2011)
4. I. Pogorelsky, V. Yakimenko, M. Polyanskiy, P. Shkolnikov, M. Ispiryan, D. Neely, P. McKenna, D. Carroll Z. Najmudine, and L. Willingale, *Ultrafast CO₂ laser technology: Application in ion acceleration*, Nucl. Instr. and Meth. A (2010), doi:10.1016/j.nima.2010.01.062
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Articles and Conference Presentations

1. N. P. Dover, C. A. J. Palmer, M. Babzien, A. R. Bell, A. E. Dangor, T. Horbury, M. Ispiryan, M. N. Polyanskiy, J. Schreiber, S. Schwartz, P. Shkolnikov, V. Yakimenko, I. Pogorelsky, and Z. Najmudin, *Optical probing of shocks driven into overdense plasmas by laser hole-boring*, [arXiv:1205.4558v2](https://arxiv.org/abs/1205.4558v2) [physics.plasm-ph]
2. I. V. Pogorelsky, M. Babzien, M. N. Polyanskiy, V. Yakimenko, N. P. Dover, C. A. J. Palmer, Z. Najmudin, P. Shkolnikov, O. Williams, J. Rosenzweig, P. Oliva, M. Carpinelli, B. Golosio, P. Delogu, A. Stefanini, M. Endrizzi, *Lasers as particle accelerators in medicine: from laser-driven protons to imaging with Thomson sources*, AIP Proceedings **1336**, 386-390 (2011)
3. I. Pogorelsky, M. Polyanskiy, V. Yakimenko, I. Ben-Zvi, P. Shkolnikov, Z. Najmudin, C. A. J. Palmer; N.P. Dover; P. Oliva, M. Carpinelli, *Proton- and x-ray beams generated by ultra-fast CO₂ lasers for medical applications*, Proc. SPIE **8079**, 80791L (2011)
4. I. Pogorelsky, M. Babzien, M. Polyanskiy, V. Yakimenko, C. Parker, N. Dover, J. Schreiber, Z. Najmudin, P. Shkolnikov, D. Neely, P. McKenna, D. Carroll, G. Dudnikova, *Monoenergetic proton acceleration with a circular polarized*

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 8. I. Pogorelsky *et al*, *Ion acceleration with picosecond CO₂ laser*, poster at APS Annual Meeting of APS Plasma Division, October 2009.
 9. I. Pogorelsky *et al*, *Ultra-fast CO₂ lasers in ion acceleration research*" oral presentation at SILAP (2009) Workshop on Super Intense Laser-Atom Physics, September 21-23 (2009), Springdale, UT, USA.
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 11. I. Pogorelsky, V. Yakimenko, I. Pavlishin, M. Babzien¹, P. Shkolnikov, A. Pukhov, L. Willingale, and Z. Najmudin, *Production of ion beams with a terawatt picosecond CO₂ laser*, Laser and Plasma Accelerators Workshop, Azores, July 2007.

Status of the field and our research

Creating compact and convenient sources of bright multi-MeV proton and ion beams is currently an especially active area of research worldwide [1, 2]. In particular, ultra-bright multi-MeV particle beams have been generated by applying high-intensity laser fields to thin foils (see e.g. a review [3] and references therein; also [4]). Our research is intended as a significant contribution to that effort and will hopefully facilitate a decisive development toward practical proton/ion sources for numerous scientific, medical, and industrial applications.

We work with a high-pressure CO₂ laser developed at BNL. The laser, while currently at the sub-TW power, with 3-4 J, 5-6 ps pulses, is potentially capable of producing up to 20 J in 1 ps pulses, that is, of attaining 20 TW power. Due to the laser pulse duration in single picoseconds, we expect its interaction with matter to be fundamentally similar to the laser-matter interaction of other TW ultrashort-pulse lasers, while substantially different from that of big, high-power nanosecond CO₂ lasers developed earlier for ICF research. In particular, the back surface of the targets irradiated by the laser remains cold and relatively intact when relativistic electrons accelerated at the front arrive – a vitally important prerequisite for the main proton/ion accelerating mechanism in solid targets [3]. Our laser adds an important new perspective to this development, not only because, with the wavelength 10 times longer, it probes the acceleration mechanisms in the parameter domain presently unattainable, but also because it promises substantial enhancements in energy efficiency and particle yield.

Our research has two major components. One is “retracing” the work already done with solid-state lasers, but with our novel laser, in order to verify its expected advantages, further investigate the physical fundamentals of the processes, and prepare the groundwork for future applications. The other is exploring entirely new regimes of laser plasma that have been opened by our CO₂ laser.

On its road to practical applications, research on laser acceleration of ions has yet to find ways to produce proton beams with a very narrow energy spectra and a rapid scaling of the ion energy with laser intensity. In a vast majority of laser-ion acceleration

experiments so far, the dominant mechanism of ion acceleration has been Transverse Normal Sheath Acceleration (TNSA). In a typical laser-ion acceleration experimental design, a linearly polarized laser beam hits a thin metal film, creates and heats plasma on its surface, and pushes relativistic plasma electrons inside the target. Emerging from the other side of the target, electrons create a strong charge separation field at the target's rear surface, which ionizes target atoms and pulls out ions. While TNSA generates bright, well-collimated, high maximum energy ion beams, the ion energy spectra are too broad for many important applications, while the maximum ion energy scales quite slowly with the laser field intensity I , approximately as $I^{1/2}$.

Based on recent theoretical developments ([5] and references therein), one acceleration mechanism seems particularly promising for generating narrow-energy spectra ion beams, Radiation Pressure Acceleration (RPA). While RPA is always present in laser plasma acceleration experiments, practically all laser-ion acceleration experiments so far have been strongly dominated by TNSA. The reason is that with the linear polarization, only at very high (unavailable yet) laser field intensities, the RPA ("piston" [6]) mechanism will become dominant. Fortunately, RPA may be investigated even with available intensities [5] if one utilizes laser beams with circular polarization, which strongly suppresses electron heating and thus inhibits TNSA and other competing processes. Our CO₂ laser provides unique opportunities for experimental investigation of RPA in its "hole boring" version [7, 8]. Indeed, for its wavelength of 10 μm , much larger than almost uniformly used $\sim 1 \mu\text{m}$ lasers, the critical plasma density is 100 times lower, which allows for using gas jets as targets. By the same token, it is qualitatively easier to observe plasma processes in the interaction region of such low-density plasma and to work close to the optimal slightly-overcritical densities. Inherently circular polarization of our laser also helps.

Current experimental setup. It incorporates the circularly polarized CO₂ laser and an optical transport system, the interaction chamber with focusing optics, target assembly, and basic ion beam diagnostics, including a magnet spectrometer and CR39 detectors. In addition to components available at BNL, custom-made at SBU, and purchased with DOE funds, an important piece of diagnostics, Thompson spectrometer, was loaned by

RAL and installed in the setup. Finally, researchers from Imperial College, London, delivered and installed components needed to work with gas jet targets. At this point, the setup looks as follows:

Figure 1. Experimental setup

The laser is focused onto the front of a hydrogen or helium gas jet from a 1 mm circular nozzle. A 10 ps, $\lambda = 532$ nm Nd:YAG laser beam, absolutely synchronized with the CO₂ laser beam, is used for probing. The time delay between driver and probe pulse is varied using an optical delay line. After crossing the CO₂ laser plasma, the probe is split and directed into shadowgraphy and interferometry channels. These give information not only about plasma creation and evolution, but also about the neutral gas jet density profile. Along the optical axis, ~ 0.7 mm above the nozzle edge, the density has an approximately triangular profile, going from zero to maximum over the length of ≈ 825 μ m. The electron density can be varied up to a maximum of $\sim 10^{20}$ cm⁻³ ~ 10 n_{cr}.

The ion beam is characterized with a magnetic spectrometer, which disperses the protons by deflecting them in a transverse magnetic field. The aperture of the spectrometer is a 0.6 mm diameter pinhole. The dispersed protons are detected with a polyvinyl toluene scintillator screen calibrated to the dose of energy deposited by protons impinging on it. The scintillator is reimaged onto an Andor EMCCD camera.

After this first successful round of experiments, our laser went out of operation for more than a year. During that time, it was substantially refurbished, moved to a more stable

wavelength, and equipped with more extensive diagnostics, including the new ability to view the temporal profile of the laser output. The main task of that renewed laser was experiments with gas jet targets.

Our earlier experiments with gas jet targets: pioneering results on proton acceleration and laser plasma physics. As we indicate above, we expect ion/proton acceleration in gas jets to provide us with a clear opportunity to demonstrate truly unique potentials of our laser. Our recent experiments, in which our friends from Imperial College, UK, played a critical role, proved that we were right in that. Working under

DOE support, we obtained the first to our knowledge experimental observation of RPA by a circularly polarized laser in an overdense gas jet, which in particular allowed for the direct experimental observations of ion acceleration by radiation pressure created by a relativistically intense circularly polarized laser radiation

In our experiments, a relativistically intense, circularly polarized CO₂ laser beam impinges upon a hydrogen gas jet and

Figure 2. Ion spectra: Selection of raw and processed proton spectra for varying peak density (n) and vacuum intensity (I) showing scaling of peak proton energy $E_{\text{max}} \propto I/n$. Parameter I/n shown to the right of the respective raw images. Shots taken with; a) $I = 7.5$, $n = 6.1n_{\text{cr}}$, b) $I = 6.5$, $n = 6.1n_{\text{cr}}$, c) $I = 6.9$, $n = 7.6n_{\text{cr}}$, d) $I = 6.7$, $n = 8.0n_{\text{cr}}$ (intensities in units 10^{15} Wcm^{-2}). e) Background subtracted (solid lines) and also corrected (dashed lines) spectra. Heights of corrected spectra adjusted to match those of raw line-outs. Line-out corresponding to b) reduced $4\times$ to fit on same scale.

generates a collimated beam of protons whose energy is concentrated in a very narrow (4%) vicinity of 1 MeV. Using gas jet targets for laser acceleration, made possible only by a long wavelength of CO₂ laser radiation, has several additional advantages, both general and RPA-specific. In particular, the low-density plasma in a gas jet lends itself to much wider array of diagnostic tools, first of all optical, and is much easier to simulate

than the much more dense plasma of interest for solid targets. At the same time, theory predicts that RPA generates highest ion energy for just-above-critical plasma density (see below), which is much easier to implement in a gas jet than in a solid target.

Figures below illustrate some of our earlier experimental results.

Figure 3. Optical probing: (a) Shadowgraphy of the interaction for $n = 4n_{cr}$, 30ps after the first main pulse interacts with the gas. Laser entered from left, with the silhouette of the gas nozzle shown above. White dotted lines approximate initial boundaries of the gas jet. (b) Density profiles obtained from simultaneous interferogram.

Figure 4. Simulations (left) and experimental shadowgram (right) of post-solitons in underdense hydrogen plasma

As you see, the proton energy spectra do display sharp peaks as predicted by RPA theory. The first research aimed to observe RPA (in a different regime of "light sail") [9] ended up

with a significantly more complicated picture, so we believe that we indeed are the first to have directly observed RPA.

Fig. 4 shows also a bubble-like structure in the plasma. This is likely one of the more important results of our experiments so far: we believe that we were the first to directly observe relativistic laser plasma solitons [10], if only in the later stages of their evolution. Figure 6 shows remarkable similarity of the observed bubble-like structures and our computer simulations of post-solitons.

Recent developments

Subsequent theoretical and experimental development [11, 12], has led to further clarification of the variety of effects that occur during laser acceleration of ions in gas jets. In particular, the UCLA group has demonstrated [12] that RPA is not the only possible acceleration mechanism in such a set-up. While in both [11] and [12] the immediate source of energy for protons is the high-speed electrostatic shock, that shock may be launched by expansion of plasma heated by the laser [12] or by the pressure of laser radiation [11], when the circular polarization suppresses electron heating. Our recent effort under the DOE support has been part of that progress.

At the center of our most recent experiments has been the interaction of an intense CO₂ laser pulse with slightly over-critical plasmas of fully ionized helium gas, which is intended as a potential source of pure alpha-particle beams that may find a number of applications, including cancer therapy. The overall picture painted by transverse optical probing is as follows. A pronounced recession of the front plasma surface with an initial velocity $>10^6$ m/s indicates by hole boring by the laser pulse. The resulting radiation pressure drives an electrostatic shock wave inside the overcritical area. This (collisionless) shock propagates through the plasma, dissipates into an ion-acoustic solitary wave, and eventually becomes collisional as it slows further. These observations, supported by PIC simulations, lead us to the conclusion that monoenergetic protons observed in our earlier reported experiment with a hydrogen jet result from ion trapping and reflection from a shock wave driven through the plasma by the laser field.

Upon reaching the region of critical plasma density, the laser pulse will stop its propagation and transfer its momentum to the plasma layer of the Debye thickness $\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}}$, which is normally just a couple of laser wavelengths. Pushed by the laser field, this layer will continue propagating through the target in the so called “hole boring” regime [11] at the velocity $v_{hb} = \sqrt{(1 + R)I/\rho c}$, where R is the target reflectivity and ρ is the local mass density, and launches an electrostatic shock that may have even higher speed, $v_{sh} \geq v_{hb}$. The shock reflects upstream ions at the double velocity, $2v_{sh}$.

This variant of RPA, which generates quasi-monoenergetic ion beams via laser-driven shock-wave acceleration (LSWA) has been recently realized using the combination of a CO₂ laser and supersonic hydrogen gas jet that easily matches the 10- μ m laser’s critical plasma density 10^{19} cm^{-3} [11]. Due to this low critical density, the shock velocity is relatively high, which accounts for multi-MeV proton beams generated at relatively moderate laser intensities of $\sim 10^{16} \text{ W/cm}^2$.

In our gas-jet acceleration experiments, plasma is transparent to the visible light, which allow us for the first time to utilize optical diagnostics for detailed study of plasma evolution during the laser acceleration process. This study is important for better understanding of the plasma dynamics pertinent to the SWA process, such as hole boring and shock wave propagation, as well as for optimizing the SWA for applications.

In our most recent publication [13], we have analyzed optical probing of helium laser jet plasma, which may serve as a source of pure alpha-particle beams with applications to e. g. cancer therapy. By varying the delay of the optical probe relative to the IR laser pulse, we observe three separate phases in the shock evolution: (i) Initially, hole-boring creates an electrostatic double layer, which accelerates background ions; (ii) Once the laser stops, positive ion reflection from the propagating double layer causes it to decelerate rapidly; (iii) As the shock speed decreases, the ion mean free path also decreases and the shock eventually becomes collisional. These findings are supported by particle-in-cell (PIC) simulations.

The experiment was performed using our $\lambda = 10.6 \mu\text{m}$ sub-TW CO₂ laser. The laser was circularly polarized. Streak-camera images of the laser output time profile revealed a train of pulses caused by spectral modulation of the pulse in the gas amplifiers, each of

~6ps length (FWHM) and ~18ps pulse-to-pulse distance. On average, 70% of the energy was in the leading two pulses, with a total integrated energy of 2-3 J. The pulse was focused by an off-axis parabolic mirror to a spot size of $w_0=70 \mu\text{m}$, giving a peak intensity $I=5\times 10^{15} \text{ Wcm}^{-2}$ with normalized vector potential $a_0=0.55$. The laser focus was placed 0.7 mm above a 2 mm-diameter gas-jet nozzle. This produced a neutral gas density profile approximated by a trapezoid with plateau width 1.6 mm and ramp width of 0.4 mm observed via transverse optical interferometry.

The probe, a frequency-doubled (532 nm) Nd:YAG laser beam passed orthogonally through the plasma before being split; one part was imaged directly onto a CCD for shadowgraphy, and the other passed through a Mach-Zender interferometer to diagnose plasma density. The timing between the CO₂ laser pump and YAG laser probe pulses was varied using an optical delay line. An example of optical probe images obtained is shown in Fig. 5. A bright sharp feature in the shadowgram (Fig. 5a) highlights the area of rapidly changing refractive index. Converting the experimentally recorded interferogram (Fig. 5b) into the integral phase map (Fig. 5c) followed Abel inversion under the assumption of the radial symmetry, we ultimately obtain the plasma density map (Fig. 5d). This reveals a sharp feature visible on a shadowgram ahead of a low-density region caused by the laser boring a hole into the plasma.

Figure 5. Typical a) shadowgraphy and b) interferometry images for delay time $\Delta t=500\text{ps}$, $n_e=1.8n_{cr}$; c) phase diagram reconstructed from the interferogram (b) (color scale in radians); d) plasma density map of the area inside a black square on (c) obtained by Abel inversion (color scale in n_{cr}). CO₂ laser enters from left.

The long horizontal features seen on the right hand side of Fig. 5a are likely due to laser filamentation during the initial stage of the gas target ionization. Once sufficiently ionized, the plasma becomes opaque ($n_e > n_{cr}$) and the laser light is reflected at the critical

surface. Its (radiation) pressure on the plasma launches a shock into the initially relatively cold plasma, as can be clearly seen by the sharp, semi-circular feature visible in Fig. 5a.

Two probe timing scans were taken for peak densities $n_e \in (1.8, 3)n_{cr}$. The distance of shock propagation from the initial critical surface position thus obtained is plotted in Fig. 2a as a function of time. The shock initially moves rapidly into the plasma before slowing at later times, with initial shock velocity higher for lower density. The estimated hole-boring velocity $v_{hb}=1.5 \times 10^6$ m/s is indicated, slowing to $v_{sh} \approx 5 \times 10^4$ m/s for $t=500-1700$ ps, for both $n_e \approx 1.8 n_{cr}$ and $3n_{cr}$. The ion mean-free-path due to (ion-ion) collisions for ions with $v=v_{hb}$ is $l_{mp} \approx 30$ mm [13] indicating that the shock must initially be collisionless. At the latest times measured, as the shock slows, $l_{mp}(\propto v^4)$ decreases significantly, and collisions play a role in dissipation.

Figure 6. Shock propagation distance z_{sh} with time from shadowgrams for $n_e \in (1.8, 3)n_{cr}$ (green triangles, black diamonds). Red solid line indicates initial v_{hb}

As already mentioned, this data was taken using pressurized helium gas. Although the acceleration of alpha particles could be useful for some applications, one of the main attractions of gas jet targets is the possibility to create impurity free beams of energetic protons, which still eludes laser-plasma acceleration from solid targets without using a post-accelerating structure. Due to the lower ionization potential of hydrogen, the laser plasma volume is larger in H than in He, especially at the jet's fringes, which can make it difficult to see fine detail. However, it is still possible to see clear shock-like structures (Fig. 7). These two images are from the same shot, where the probe split into two different polarizations with a relative delay to better investigate the plasma dynamics.

Fig. 7a was taken ~ 130 ps Fig. 7b taken 430 ps after the interaction, during which time the shock-like structure moves forwards at an average speed of $\sim 10^5$ m/s, which is comparable to the velocity seen for the helium data-set.

Figure 7. Two shadowgraphy images from the same shot using a hydrogen gas target instead of helium; a) at $\Delta t = 130$ ps after the laser plasma interaction, and b) at $\Delta t = 430$ ps.

To further investigate the hole boring and shock wave behavior during the LSWA process, numerical simulations of the interaction were performed using particle in-cell (PIC) codes. 2D3V simulations were performed with the code OSIRIS [14]. The parameters of the simulation were as follows. A circularly polarized $\lambda = 10.6 \mu\text{m}$ pulse, with $\tau = 5$ ps, $a_0 = 0.55$, $w_L = 70 \mu\text{m}$ was focused into a fully ionized, initially cold ($T_e = T_i = 0$) He plasma of density $n_e = 1.8 n_{cr}$. The plasma was assumed with a step-like density gradient. Fig. 8 shows the plasma ion charge density from the simulation at different times. The first two frames, at 2 and 4 ps into the interaction, show a density increase at the front along with the cavity formed by the hole-boring, in agreement with what is seen experimentally. The front is formed by radiation pressure displacing plasma electrons in the collisionless skin-depth. The ions, which due to their greater mass are unaffected by the laser fields, accumulate at the front due to the space charge field of the ensuing electrostatic double layer. The large electrostatic field associated with this front also accelerates upstream ions. This leads to the formation of a large population of energetic ions that can be seen to outrun the shock front in Fig. 8a. Since the plasma ahead of the front is initially cold, hole-boring causes a compression of the plasma. The piston-like effect of the radiation pressure launches a shock into the plasma. The shock front is seen in Fig. 8 propagating into the plasma, even after the laser pulse stops interacting with the

plasma (Fig. 8c). Although initialized cold, the plasma temperature is elevated by vacuum heating, due to the buckling of the front surface from hole-boring. Hence for lower n_e , where hole-boring is faster, the rate of heating increases more rapidly, and the shock moves faster.

Figure 8. Charge density distribution from 2DPIC for $n_e=1.8n_{cr}$, $T_{ei}=0$ at a) $t=2$ ps, b) 4 ps and c) 7 ps after the start of the interaction, where the laser pulse is 5 ps long. Density scale same for all images and in units of n_{cr}

For the high initial electron temperature $T_{ei}=50$ keV, when v_{hb} is only slightly above the initial sound speed, $c_s = \sqrt{kT_e/m_i}$, a series of solitary waves are pushed into the plasma. Decreasing the initial temperature of the simulation to 5 keV increases the ratio of piston velocity to the local sound speed, and the ion density profiles (Fig. 9d) show the formation of a high density shock. The shock moves at $v_{sh} \approx 4 \times 10^6$ m/s ahead of the critical surface that propagates at $v_{hb} \approx 3 \times 10^6$ m/s. The electron density at this shock can be as high as $n_e=10 n_{cr}$. Fig. 9d shows that the shock width ($\sim c/\omega_p$) is less than $1 \mu\text{m}$, which is why, though it is clearly visible from shadowgraphy (Fig. 5a), it is not properly resolved in the interferogram (Fig. 9b-9d). The potential of this front is large enough (0.15 MV) that the associated electric field, which reaches $>200 \text{ GV/m}$ (Fig. 9f), efficiently reflects $\sim 50\%$ of upstream ions. Phase space diagram (Fig. 9e) shows that the reflected ions gain a speed of $2v_{sh}$ by “bouncing” off the shock front. Whilst the laser is active, it is v_{sh} that determines the accelerated ion velocity (not v_{hb}). This results in a remarkably narrow energy spread for the reflected ions [11, 12].

At a relatively cold electron plasma ($T_{ei} < 1$ keV), $v_{hb} < c_s$ a region of high ion density is formed right at the hole-boring front, creating a double layer which reflects nearly 100% of upstream ions. This situation is illustrated by the top row of plots in Fig. 9. Indeed, for $T_{ei}=0$ any moving non-charge neutral density perturbation can cause a shock, and therefore the ions reflected at the front surface show some interesting features, seen in Fig. 9b and 9c. This secondary shock disappears when the temperature is increased slightly, and is therefore an artifact of the 1D simulation with circular polarization, with the background temperature staying near $T_{ei}=0$.

Figure 9. Longitudinal distributions of a,d) charge density, b,e) ion velocity, c,f) electric field and potential for $T_{ei}=0$ (top) and $T_{ei}=5$ keV (bottom) from 1DPIC at the end of the laser pulse ($t=5$ ps) for $n_e=1.8n_{cr}$

At the end of the laser pulse, the potential associated with the shock is still sufficient to reflect ions. However, as there is no longer a pressure being exerted by the laser, this particle reflection reduces the energy of the ion front, causing it to slow until reaching a critical Mach number, M_s , where particle reflection practically stops. Assuming $T_i=0$, one expects a lower limit of $M_s=1.6$ from an isothermal approximation for the plasma,

whereas assuming maximum electron trapping behind the shock gives an upper value of $M_s \approx 3$.

The reported experiment and simulations show three separate regimes of laser interaction with the overdense near-critical plasma: 1) for $v_{hb} \leq 3c_s$, the laser launches waves into the plasma from which there is no ion reflection; 2) for $v_{hb} > 3c_s$, an electrostatic collisionless shock is formed, moving ahead of the hole-boring front with partial particle reflection; and 3) for $v_{hb} \gg c_s$ there is 100% reflection at the double-layer formed at the front surface and $v_{sh} \sim v_{hb}$.

As the 1D simulations show, there is a smooth transition between hole-boring and shock acceleration. The main difference is that for shock acceleration some ions are transmitted (and don't reach high energies) and some are reflected (reach high energies). The fraction of reflected ions is 100% for hole-boring, but for shock acceleration it varies, and can be very low for fast moving shocks. When considering the interaction as a source for a laser plasma ion accelerator, there is therefore a tradeoff between higher maximum energies from hotter plasma, where a small fraction of the particles are accelerated up to higher energies, and higher efficiency from a colder plasma where all the particles are accelerated to a smaller maximum energy. This might explain the larger flux of accelerated protons observed with a short, circularly-polarized laser beam [11], as opposite to a longer, linearly-polarized driver where heating is stronger [12].

The dynamics of the shock driven into an overdense target due to hole-boring we have observed, with its phases changing gradually from the electron-ion double-layer to an ion acoustic soliton and finally to collisional shock, provide insight into the dynamics of shock acceleration in plasmas, which may prove to be a promising route to highly energetic ion production.

Conclusion: immediate plans

1. CO₂ laser development.

Increase laser power.

2. Laser proton acceleration in gas jets

This direction, already outlined in our initial proposal, has acquired a much higher priority after the first successes achieved under DOE support. In addition to numerous practical advantages such targets promise (versatility, non-destructive nature, availability of materials which are not solid under easily attainable conditions), they allow a much easier avenue to understanding the physics of the laser ion acceleration. In this regard, investigation of relativistic plasma solitons is of particular interest.

3. TNSA in metal foils

Finally, we, of course, intend to continue full-speed our experiments on generating MeV protons and ions in metal foils as at this point most straightforward avenue to high-intensity, high-energy proton/ion beams. While we work on increasing the available laser intensity, we will conduct experiments with linearly polarized normal-incidence laser beam. This would allow for the most straightforward comparison with TNSA models and results obtained with shorter-wavelength lasers.

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