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First Experiments on Laser Acceleration of Protons in Overdense Gas Jets

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Abstract We report the first, to our knowledge, experimental investigation of proton acceleration by a laser in an overdense gas jet, in particular first direct experimental observations of quasi-monoenergetic spectra of ions accelerated by radiation pressure of relativistically intense circularly polarized laser radiation. CO_2 laser radiation with the wavelength $\lambda \approx 10$ µm, focused to the intensities of up to 10^{16} W cm^{-2} into a hydrogen gas jet with densities of 3-5x10^{19} cm^{-3} , generates proton beams with energy in a narrow range around 1.2 MeV, in a reasonable agreement with Radiation Pressure Acceleration theory. We also observed slow-moving, quasi-stable bubble-like structures in laser plasma, which we interpret as post-solitons.

Keywords: ultrafast lasers, ion acceleration
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INTRODUCTION

In a typical laser-ion acceleration experiment so far, a linearly polarized, relativistically intense laser beam heats electrons in plasma on a surface of a thin metal foil and pushes them through the target. Emerging from the cold rear surface, electrons create a strong charge separation field, which ionizes target atoms and pulls out ions. Because the field is strong and the surface is well defined, ion beams produced through this Transverse Normal Sheath Acceleration (TNSA) [1] are well-collimated and bright, and the proton energy as high as 68 MeV has been attained. However, the energy spread of TNSA beams is too broad for many important applications, and the scaling of maximum energy with the laser intensity is quite slow.

A different acceleration mechanism, Radiation Pressure Acceleration (RPA), may hold a better promise both in terms of the energy spectra width and faster scaling with the laser intensity. In most of experiments so far, however, RPA has played a minor role, being completely overshadowed by TNSA. It has been predicted long ago that RPA may dominate ion acceleration at very high intensities, which are not readily attainable with present lasers. Recently, an alternative way to explore RPA was proposed: using circularly polarized laser radiation [2]. When such radiation impinges upon a target surface, it does not heat electrons; thus, TNSA is strongly suppressed. Instead, laser radiation pushes "cold" electrons inside a target, thus creating a charge separation field that accelerates ions. Depending on the amplitude and the duration of the laser pulse and on the target thickness, the RPA acceleration may manifest itself as "hole-boring" [3] (thick targets) or "laser piston" [4] (ultra-high intensity in relatively thick targets). A piece of an ultra-thin (sub-wavelength) target could be accelerated as a whole to GeV/ion energies by high-intensity laser pulses "light-sail" regime [5]. In all its ramifications, however, RPA is expected to deliver narrow energy spectra and fast (almost-linear) growth of maximum ion energy with the laser intensity.

The first dedicated experiments on RPA [6], intended to explore the light-sail regime, reported significant problems with solid targets. In particular, the predicted narrow energy spectra were actually masked by significant broadening, most likely because of the deformation of the target by the laser pulse.

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A CO_2 laser provides unique oppurtunities for experimental investigation of RPA, because its wavelengh of 10 μm allows for using gas jets as overdense targets. Subsequently, it becomes much easier to observe plasma processes in the interaction region and to work close to the optimal (slightly-overcritical) densities. We report the first to our knowledge experimental investigation of proton acceleration by a laser in an overdense gas jet, in particular first direct experimental observations of quasi-monoenergetic spectra of ion accelerated by radiation pressure created by a relativistically intense circularly polarized laser radiation. CO_2 laser radiation with the wavelength $\lambda \approx 10$ μm, focused to the intensities of up to 10^{16} W cm^{-2} into a hydrogen gas jet with densities of $3\text{-}5\times10^{19}$ cm^{-3} generates proton beams with energy in a narrow range around 1 MeV, in a reasonable agreement with the RPA theory. We also observed slow-moving, quasi-stable bubble-like structures in laser plasma, which we interpret as post-solitons.

RADIATION PRESSURE ACCELERATION IN GAS JETS

While the RPA theory has been developed, experimental capabilities to probe the process remained extremely limited. Indeed, a natural medium for RPA is overdense laser plasma. For widely used near-IR lasers ($\lambda \sim 1$ μm), such plasma is, however, way too dense for most conventional diagnostics, especially for optical probes, because it reflects, absorbs, and/or strongly distorts visible light. As a result, the only practical tool for investigating plasma processes during the acceleration is probing with proton beams generated by laser acceleration [7]. While already producing interesting results, this tool is complicated and not easily visualized.

Our then-unique, ultrafast Terawatt CO_2 presented another possibility. For λ=10 μm, the critical plasma density is $\sim 10^{19}$ cm^{-3}. Such plasma is perfectly transparent for visible light, thus allowing for simple imaging and interferometry. Although laser acceleration experiment have been conducted already with relatively low-density plasma prepared by laser ablation of solids [8], the easiest and most promising way to investigate laser ion acceleration by RPA is by using gas jet targets. Indeed, it is quite easy to obtain and control the required gas jet density; and acceleration mechanisms competing with RPA, such as TNSA, are very weak in a plasma jet even with linear polarization (due mainly to the slow plasma density gradients). Moreover, gas jets as laser acceleration targets have numerous potential practical advantages: a one-species ion (e. g. proton) beam may be generated; the target is non-destructible and creates no debris; non-solid elements may be used; etc.

Out of the three RPA modes outlined above, only one, "hole-boring," is applicable to our experiments. Fortunately, theory [6] provides us with a good quantitative estimate for the ion energy and the number of accelerated ions. For non-relativistic ions, the ion energy spectra are expected to be concentrated around the maximum expected ion energy at:

$$E_{\max}/m_i c^2 \approx 2(Z/A)(m/m_i)(n_c/n_e)a_0^2\,, \tag{1}$$

where m and m_i are electron and ion mass, respectively; Z and A are ion charge and atomic mass; n_e is the electron density in the area where the acceleration takes place; $n_c=\pi/(r_e\lambda^2)$ is the critical electron density, $r_e \approx 2.8\times10^{-13}$ cm is the classical electron radius; $a_0 \approx 0.36\ I_{18}\ \lambda^2(\mu\text{m})$ is the dimensionless laser field intensity for circular polarization, I_{18} is the laser beam intensity in units of 10^{18} Wcm^{-2}. For the number of accelerated ions, the same model yields

$$N \approx S n_{i0} \lambda / 4\pi\,, \tag{2}$$

where S is the laser focus area, and n_{i0} is the ion density in the area of acceleration. For protons, Eq. (1) reduces to:

$$E^p{}_{\max}(MeV) \approx (n_c/n_e)a_0^2 \tag{3}$$

It is also important that, as computer simulations show [9], these estimates may not be significantly affected by imperfection of the circular polarization (some ellipticity which is present in our CO_2 beam) or by the plasma density gradient, rather than sharp plasma border, that is obviously the case for gas jet targets. Moreover, for a slow plasma gradient, we may expect most of the acceleration to occur near the critical plasma density area, $n_e \approx n_c$, which leads to further simplifications:

$$E^p_{\max}(MeV) \approx a_0^2 \tag{4}$$

Simultaneously, for typical focusing conditions $S=\nu\pi\lambda^2$, where $\nu\approx3\text{-}10$, Eq. (2) can be reduced to $N \approx \nu\pi^2\lambda / r_e$, where r_e is the classical electron radius. Both $E^p_{\max}$ (for constant intensity) and N scale favorably with the laser wavelength, illustrating the merits of a CO_2 laser for ion acceleration.

CO_2 LASER ACCELERATION IN A HYDROGEN GAS JET: EXPERIMENTAL SETUP AND RESULTS

We have undertaken a series of experiments on CO_2 laser acceleration of protons in hydrogen gas jets. The experimental setup is depicted in Fig. 1. A 1-TW, 5-ps CO_2 laser pulse has been focused with the f/3 parabola onto the front surface of a hydrogen gas jet from a 0.5 mm circular nozzle. We estimate the maximum CO_2 intensity attained in our experiments at about 2×10^{16} W/cm^2. A 10 ps, green (λ = 532 nm) Nd:YAG laser pulse, synchronized with the CO_2 beam, was used for probing. The probe pulse delay was varied using an optical delay line. After passing through the plasma perpendicular both to the jet and to the CO_2 beam, the probe was split and directed into shadowgraphy and interferometry channels. These not only gave information about plasma creation and evolution, but also provided the neutral gas density profile. Along the optical axis, ~ 0.5 mm above the nozzle edge, the gas density had an approximately triangular density profile. The density of hydrogen atoms could be varied up to a maximum of ~ 10^{20} cm^{-3}. The ion beam was characterized with a magnetic spectrometer. The dispersed protons were then detected with a scintillator screen calibrated to the energy deposited by protons. The scintillator was imaged onto an Andor EMCCD camera.

Sample registered proton spectra are given in Fig. 2. As predicted by RPA theory, they are narrow, the narrower the higher the energy. As to the maximum proton energy we observe, 1.2 MeV, it seems somewhat too high for our CO_2 laser intensity available, if Eq. (4) is to be believed. One possible explanation of this discrepancy is that we observe extensive beam filamentation at high intensities, and the laser field inside the filaments was presumably much higher that the ambient field. Optical diagnostics available for our experiments enabled us to register spectacular images of the hole-bring process that underlines the acceleration (Fig. 3).

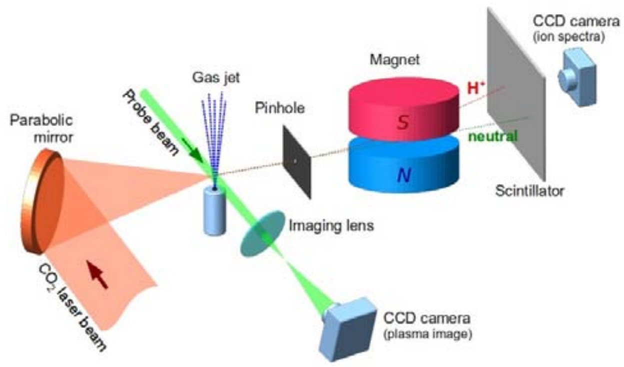

FIGURE 1. Experimental setup for laser proton acceleration in a gas jet.

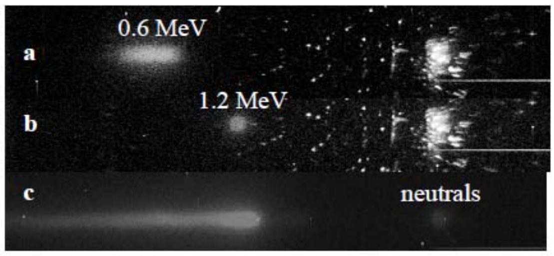

FIGURE 2. Sample raw spectra: a) and b) obtained with a gas jet, c) for comparison, a TNSA spectrum obtained previously from a thin Al foil.

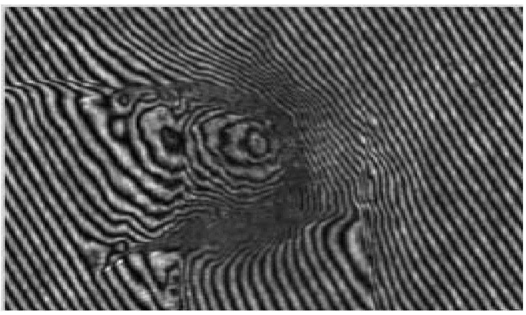

FIGURE 3. Sample interpherogram of laser hole-boring in jet plasma. CO_2 beam propagates from left to right.

DIRECT OBSERVATION OF LASER PLASMA POST-SOLITONS

During the experiments described above, the availability of optical imaging enabled us to directly observe striking features: slow moving cavities created in under-critical hydrogen plasma by a relativistically intense picoseconds CO_2 laser radiation. We believe that these cavities are "post-solitons" which descend from laser-plasma solitons, and that our experiments provided first direction observations of post-solitons.

Formation of nonlinear quasi-stable structures in laser plasma at relativistic laser intensities has long being predicted. Most promising for experimental observation are slow-moving solitons in underdense [10] and overdense [11] plasmas. Even those solitons, however, are notoriously difficult to observe. For one, the predicted size of these objects is quite small, of the order of the plasma skin depth, which is close to the laser wavelength in near-critical plasma; that is, for a typical near-IR laser, just a few microns. Moreover, they are quasi-stable only on the time scale of ω_e^{-1} where ω_e is the plasma frequency, while evolving on the time scale of ω_i^{-1}, $\omega_i^2 / \omega_e^2 = m_e/m_i$, which is typically in picoseconds. On top of this, the diagnostics available for high density plasma of most interest for soliton observations are very limited. In particular, optical diagnostics, most direct and usually most accurate, are basically out of question, because visible light is reflected, absorbed, or severely distorted in such plasma. As a result, no experimental observations of laser-plasma solitons have been reported so far.

A decade ago, Naumova *et al*. [12] draw attention to other laser-plasma objects, "post-solitons," that directly evolve from solitons. Post-solitons are much larger objects, typically spherically shaped, with much higher electromagnetic field strength and much lower electron density inside than outside. Even such relatively large objects, are, however, difficult to directly observe in near-critical plasmas created for usually employed relativistically intense lasers in near IR. The only publication that reported successful observation of post-solitons [6] was in fact using the patterns of propagation of laser-accelerated protons to infer the existence of post-solitons in the plasma.

The slow-moving bubble-like structures (Fig. 4) we clearly see in the green light are very similar to those indirectly observed by Borghesi et al [7], which is an important confirmation of our and their results. Our computer simulations support our conclusion that we indeed observe post-solitons. Notably, the laser intensity in our experiments is 3 orders of magnitude lower that the intensity in [7]. With only two orders accounted for by the 10 times larger wavelength, this difference suggest a quite low threshold of soliton formation. We also observe (Fig. 4) the affinity of soliton formation and filamentations hypothesized in [7], as well as the likelihood of multiple soliton formation in wide and long pulses.

CONCLUSION

Our first experiments with laser acceleration in overdense gas jets have demonstrated important potentials of using a mid-IR (CO_2) laser and the resulting availability of optical diagnostics. With still modest laser intensity available, we were able to directly observe, for the first time, RPA by circularly polarized lasers and quasi-stable laser plasma structures (post-solitons).

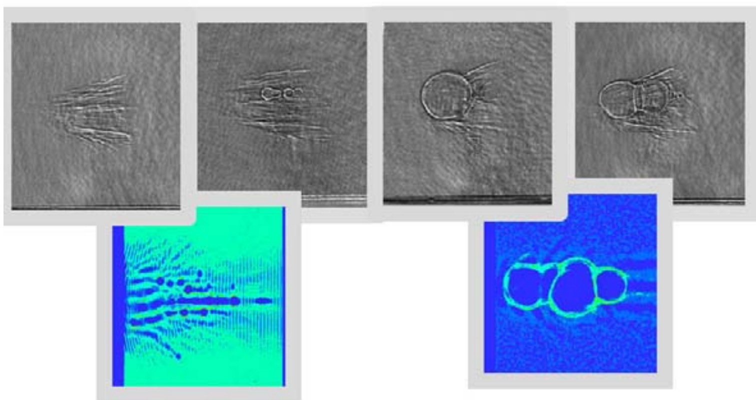

FIGURE 4. Post-solitons and filaments in CO_2-laser plasma in a gas jet: experiments (top) vs simulations (bottom).

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