SPECTRAL BROADENING OF IONS ACCELERATED BY A RADIATION PRESSURE DRIVEN SHOCK *

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Abstract

Laser driven ion acceleration has been the focus of considerable research efforts since multi-MeV energies were first demonstrated. Most experiments use solid state laser pulses focused onto thin foil targets. However, recent progress in CO_2 laser technology allows for the creation of intense pulses at lambda ∼10 μm. The longer wavelength permits the use of low density targets. In these conditions ion acceleration is primarily driven by a shock wave due to the radiation pressure of the laser. This acceleration mode has the advantage of producing narrow energy spectra while scaling well with laser intensity. New improvements to the CO_2 laser at the Accelerator Test Facility allow for the unique production of a single picoseconds-scale pulse with 1TW peak power. We report on the interaction of an intense CO_2 laser pulse with overdense hydrogen and helium gas jets. Using a two pulse optical probe, we are able to obtain real-time density profiles at different times during the interaction, allowing for the characterization of shock wave velocities and peak density conditions. Ion energy spectra are measured using a Thomson spectrometer and scintillating screen.

INTRODUCTION

Acceleration of protons by intense laser pulses has become an increasingly active area of study amongst nuclear, plasma, and accelerator physicists. Considerable progress has been made using thin foils as targets for high intensity lasers at optical wavelengths [1] [2] . These experiments utilize the highest intensity lasers to reach the highest proton energies, but at the expense of beam quality and energy spread.

An alternative is to use the radiation pressure of the laser to drive hole-boring or shock wave acceleration of ions from a low density target. The ponderomotive force of the laser can drive plasma electrons in an underdense plasma further into the target, forming a critical surface. For a cold electron population, hole-boring acceleration takes place. The plasma critical surface recedes at the hole-boring velocity, v_{HB}, reflecting ions at a velocity of $2v_{HB}$. Recent experiments with intense, circularly polarized, CO_2 laser pulses have demonstrated hole-boring acceleration by producing collimated bunches of protons with energies greater than 1 MeV and narrow energy spread [3] [4].

In the case of a hot electron population, the strong charge separation at the critical surface launches a shockwave into the plasma, which reflects ions at nearly twice the shockwave velocity [5]. This mechanism requires a high electron temperature to reach high shock velocities. Collisionless shockwave acceleration has been shown to similarly produce quasi-monoenergetic proton beams [6].

Improvements to the CO_2 laser system at Brookhaven National Laboratory's Accelerator Test Facility have allowed for the production of ps-scale single pulses with TW peak power [7]. We report on the acceleration of protons using intense linearly polarized CO_2 pulses. With two pulse optical probing, we measure peak densities and shock wave velocities, while ion spectra are measured using a scintillator and Thomson spectrometer. Observed profiles correlate with 1D PIC simulations predicting declining shockwave velocity immediately following the laser plasma interaction (LPI).

EXPERIMENTAL METHOD

Utilizing a isotopic CO_2 mixture in a regenerative amplifier, we amplify a 10.2 μm CO_2 pulse centered on the R-branch of vibrational transitions. The pulse passes through a 10 bar amplifier resulting in a single 5 ps pulse providing a maximum of 1 TW power [7]. The pulse is then focused with an $f/3$ off-axis parabolic mirror to a focal spot of $w_0 = 50$ μm, providing a maximum on-target intensity of $I \sim 3 \times 10^{16} W cm^{-2}$ corresponding to $a_0 = 1.5$. The laser contrast is $> 10^5$ as measured by an infrared power meter.

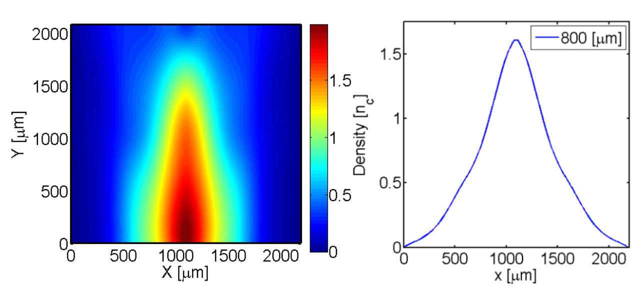

Figure 1: H_2 neutral density from a 1 mm nozzle at 15 bar backing pressure. Right, the density profile 800 μm above the nozzle.

We use 1 mm and 2 mm cylindrical nozzles to produce high density gas jets. Figure 1 shows the neutral density for H_2 gas with a backing pressure of 15 bar. A lineout is taken at 800 μm from the nozzle, showing a peak density

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of $1.5 \times 10^{19} cm^{-3}$ along the laser axis, with an underdense absorption region upstream of the laser focus. The critical density for a 10.2 μm laser is $1.06 \times 10^{19} cm^{-3}$.

A frequency-doubled 532 nm YAG pulse is split into two 14 ps probe channels for plasma diagnostics, as shown in Figure 2. Each pulse interacts with the plasma transverse to the laser axis, with a variable delay of 50 ps to several ns achievable between pulses. One beam is used for shadowgraphy; the resulting image provides highlights areas of rapidly changing density, due to the dependence on the 2nd-derivative of refractive index. The other is sent through a Mach-Zehnder interferometer, providing a density dependent fringe pattern.

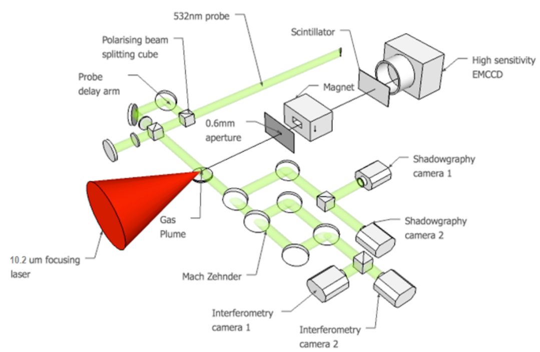

Figure 2: Optical probing arrangement.

The accelerated ion beam is filtered through a 600 μm pinhole before being dispersed by a Thomson spectrometer. The corresponding solid angle seen by the pinhole is 1.2×10^{-5} sr. The beam is dispersed according to momentum by a 5 cm magnet, while a 6.4 cm long electrode provides an adjustable electric field for displacing different ion charge states, if needed. The dispersed beam strikes a 0.5 mm thick sheet of BC-408 polyvinyl toluene (PVT) based scintillator. Photon yield calibrations have been performed using low energy protons at the Stony Brook Tandem Van de Graaf [8]. Scintillation light is imaged by a Princeton ProEM+ EMCCD camera.

PROTON ACCELERATION WITH NARROW ENERGY SPREAD

The ion beam profile is near Gaussian in both spectral and transverse directions, the latter of which is caused by passage of the beam through the pinhole along the laser axis. We can deduce the instrument function of the pinhole from this transverse spread, allowing us to calculate a true spectral profile of the beam. The obtained spectrum is shown in Figure 3. The central energy of the beam is measured at $\sim$ 1.6 MeV with a 12% FWHM energy spread. Using our calibrated BC-408 yields, we observe $\sim 8 \times 10^{9}$ protons/MeV/sr.

For this particular shot, the H_2 backing pressure is 12 bar, leading to peak neutral densities of $1.5 \times 10^{19} cm^{-3} \simeq$ 1.4 n_c. We measure a laser pulse energy of 4.34 J on target, corresponding to $a_0 = 1.25$. The predicted hole-boring velocity at this intensity and density is $v_{hb} \approx 8 \times 10^{6} ms^{-1}$, resulting in a kinetic energy of 1.3 MeV, less than the observed proton energies. We also measure the proton density using interferometry taken 132 ps after the beginning of the LPI. By performing an inverse Abel transform on the target's phase map, we obtain electron density profiles of the plasma, as shown in Figure 4.

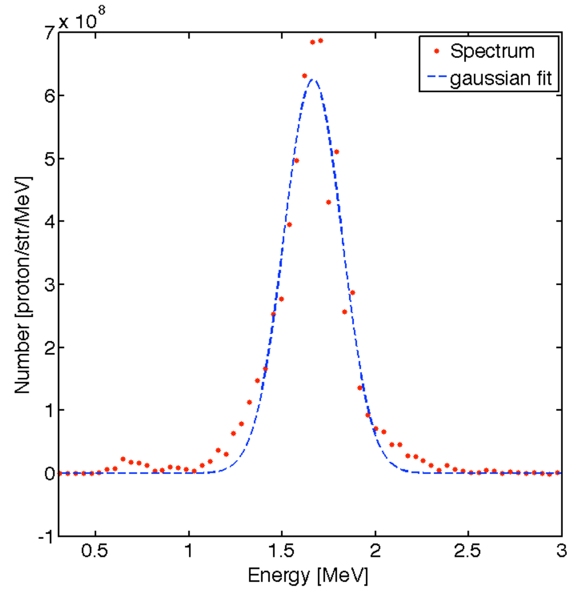

Figure 3: Proton energy spectrum shows a well defined peak at 1.6 MeV with a 12% FWHM energy spread.

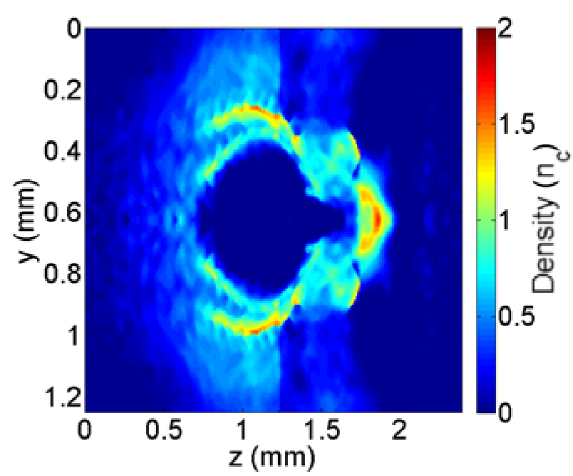

Figure 4: Time resolved interferometry reveals the plasma density distribution at 132 ps after the LPI begins. The laser travels left to right.

SHOCKWAVE VELOCITY EVOLUTION

We observed many instances of accelerated protons possessing a broad energy spectrum under the same experimental conditions as described above. Figure 5 shows a combined spectra of protons accelerated by similar laser intensities. Single shot outcomes are strongly sensitive to

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target conditions [9]. In particular, the laser pre-pulse has a significant effect on the ion spectrum by tailoring the density profile prior to the arrival of the main pulse. This effect will be discussed in detail in a future publication.

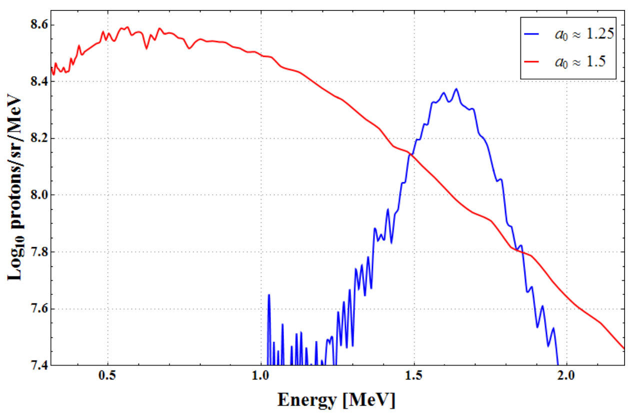

Figure 5: A comparison of measured proton spectra with listed laser intensities.

We performed 1D PIC simulations using EPOCH to investigate time dependence of shockwave velocity. Simulations were performed using 1300 cells at 100 particles per cell within a 500 μm simulation box. Figure 6 shows the proton density evolution through an infinite slab of cold plasma with density $2n_c$ after irradiation by a 1 TW pulse. Collisions are included in the simulation processes.

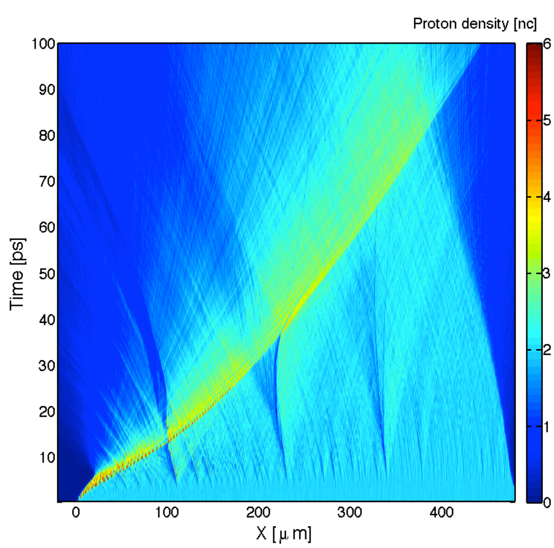

Figure 6: Particle density plotted from 1D PIC simulations.

These simulations show a clear decline in shockwave velocity beginning within the first few ps beyond the LPI. A significant reduction in peak ion density is also predicted by the simulation. The decay of the shockwave velocity modifies the accelerated proton spectra as protons are reflected at lower energies. The resultant spectra are highly dependant upon the duration in which ion reflection occurs. Energy spectra predicted by PIC simulations document the degradation of ion spectra with time and are shown in figure 7. A lengthened ion reflection period would suggest an increase in the total number of ions accelerated, which is consistent with observed spectra in figure 5.

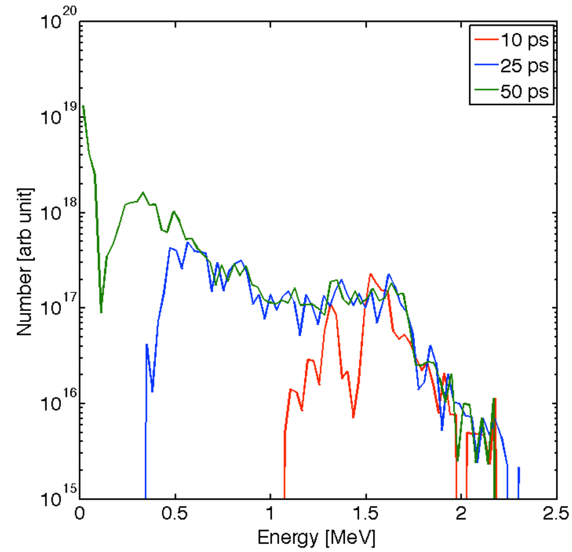

Figure 7: Simulated ion spectra extracted at different times after the LPI.

CONCLUSION

We have reported the production of high purity proton beams from the interaction of a single, linearly polarized 10.2 μm CO_2 pulse with near critical density Hydrogen gas. Peak proton energies correlate well with those predicted by radiation pressure models. Interferometry taken immediately following the LPI show the creation of a high density shock which propogates into the plasma. However, a broad swath of proton energy spectra are measured, providing evidence of rapid decline of shockwave velocities. These findings are corroborated by 1D PIC simulations with comparable experimental parameters. Our results emphasize the importance of target profile and LPI timeframe in accelerating ions with a narrow energy spread.

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