PROTON ACCELERATION IN CO_2 LASER-PLASMA INTERACTIONS AT CRITICAL DENSITY*

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Abstract

Over the last several years, the Target Normal Sheath Acceleration (TNSA) mechanism in solid density plasmas produced by a laser pulse has achieved proton energies up to 10's of MeV and quasi-monoenergetic beams at lower energies. Although solid-target experiments have demonstrated high-charge and low-emittance proton beams, little work has been done with gaseous targets which in principle can be operated at a very high repetition frequency. At the Neptune Laboratory, there is an ongoing experiment on CO_2 laser driven proton acceleration using a rectangular (0.5x1.2mm) H_2 gas jet as a target. The main goal is to study the coupling of the laser pulse into a plasma with a well defined density in the range of 0.5 to 2 times critical density and characterize the corresponding spectra of accelerated protons. Towards this end, the Neptune TW CO_2 laser system is being upgraded to produce shorter 1-3ps pulses. These high-power pulses will allow us to investigate acceleration of protons via the TNSA and Radiation Pressure Acceleration mechanisms as well as their combination. The current status of the proton source experiment will be presented.

INTRODUCTION

Laser-driven ion acceleration (LDIA) has attracted interest of the scientific community due to the compact nature of the accelerator. LDIA produced ion beams, which have ultra-low emittance and short duration, have been proposed for fast ignition in inertial confinement fusion [1], as a diagnostic tool for probing the electric fields in high temperature plasmas [2], and for proton beam cancer therapy [3].

The dominant mechanism thought to be responsible for ion acceleration in these experiments is Target Normal Sheath Acceleration (TNSA). Here, an intense, linearly-polarized laser pulse is incident upon a thin solid target where it quickly heats and accelerates the electrons inwards along the target normal. Once these hot electrons exit the back surface of the target, they set up a strong electrostatic sheath field that can reach values greater than 10^{12}V/m[4]. This sheath field then produces the ion beam by accelerating ions from the rear surface of the target. This has been realized in experiments achieving proton energies up to ~58MeV and heavy ion energies up to ~430MeV using laser intensities of 5x10^{19} and 3x10^{20}W/cm^2[5, 6], respectively.

Recently, a new mechanism for LDIA called Radiation Pressure Acceleration (RPA) has been proposed in [7]. Here, circular polarization is used voiding the laser pulse of the oscillating component of the ponderomotive force which is the main source of electron heating in the case of normal incidence. This allows the electrons to be accelerated by the slowly varying component of the ponderomotive force producing a compressed electron layer which creates an electrostatic force to accelerate the ions. Simulations show that this process can continue throughout the plasma accelerating more electrons and ions, and can even continue in vacuum after the laser pulse has passed the target [8]. Therefore, a longer laser pulse is beneficial as it increases the interaction time of the laser, electrons, and ions.

Here we present an ongoing experiment at the Neptune Laboratory investigating the coupling of a high-power 10um laser pulse into a gas jet with the goal of producing a reproducible LDIA source scalable to a high repetition rate. Gas jets have the advantage of precise plasma density control in the range of 10^{18}-10^{20}cm^{-3} around the critical density at 10μm (10^{19}cm^{-3}) providing a unique parameter space for the investigation of both the TNSA and RPA mechanisms. They can also produce a reliable plasma source at a 1Hz repetition rate which is difficult when solid density targets are used. Gas jets have been used previously to study LDIA by using 1um laser pulses for which the plasma density was grossly underdense ($<.05n_c$) [9].

In a normal incidence plasma experiment, it is desirable to have laser pulses on the order of a few picoseconds or below to lessen energy reflected back from the critical density layer and coupling to underdense parametric instabilities. To this end, we have launched an upgrade of the Neptune TW CO_2 MOPA laser system to produce 10um pulses with a duration of 3ps. The status of this upgrade is presented below.

SHORT PULSE CO_2 AMPLIFICATION

Amplification of a 3ps long 10μm pulse requires a bandwidth that covers multiple rovibrational lines of the CO_2 molecule. One method to circumvent this lack of bandwidth is through pressure broadening where collisions between particles broaden the bandwidth of each rovibrational line. At very high pressures (10atm), this broadening is sufficient enough to cover the 55GHz gaps between lines resulting in a quasi-continuous spectrum spanning ~1THz. This mechanism has been demonstrated experimentally by Corkum producing ~1ps pulses with 1.5mJ of energy [10]. Recently, researchers at BNL have shown that this method can be scaled to higher energies producing 6ps pulses with ~6J of energy [11].

Although high-pressure machines provide the necessary

* This work is supported by the DOE Contract No. DE-FG03-92ER40727.

bandwidth for the amplification of picosecond pulses, stable operation requires the aperture of the discharge volume to be small, thus limiting the energy extraction. However, simulations [12] and our experiments [13] show that broadening of the spectral lines can also occur from the high fields ($\sim$10GW/cm^2) of the laser pulse itself. This is a useful mechanism as it allows one to employ a large aperture final amplifier at 2-3atm for maximum energy extraction. In the Neptune Laboratory, we plan to implement both broadening mechanisms in our CO_2 MOPA laser system to reach 1TW of power for LDIA. The CO_2 laser MOPA system consists of a TEA master oscillator, a high-pressure regenerative amplifier, and a 3atm large aperture multipass amplifier.

Short 10um Seed Production

The first stage of the laser system involves production of a short 10μm seed pulse in a two stage semiconductor switching system [10], depicted in Fig.1a. Here, a long p-polarized 10μm pulse from the master oscillator is incident upon a Ge plate at Brewster's angle. Simultaneously, a short 1μm pulse with a photon energy above the band gap of Ge is incident on the plate modulating its reflectivity via electron-hole plasma formation. Due to this, a 10μm pulse is reflected with a cut-off rise time equal to that of the corresponding 1μm pulse, and a long (ns) tail following the rate of plasma recombination. Then a second Ge plate, acting on transmission, can be used in a similar manner to slice the tail. In Fig.1b we show that the reflectivity of the 10μm pulse is increased and eventually tends to saturate as the 1μm fluence is increased. The semiconductor switching system is used to gate the 200ns long pulses from the 10μm master oscillator to $\sim$3ps containing $\sim$750nJ of energy.

For the slicing pulse, we have built a 1μm glass CPA system employing a Silicate glass oscillator (Timebandwidth GLX-200), regenerative amplifier, and two single-pass booster amplifiers. At the present time we are producing 1.6ps (FWHM) long slicing pulses containing 5mJ of energy to slice 3ps 10μm pulses. Future experiments may exploit the 200fs bandwidth of the Silicate glass system for the amplification of sub-ps CO_2 laser pulses.

Amplification via Pressure and Field Broadening

The first stage of amplification will be provided by a 10atm TE CO_2 laser having a gain volume of 1x1x60cm using a gas mix of 1:1:12 (CO_2:N_2:He). Pressure broadening at 10atm ensures a quasi-continuous bandwidth of 1THz which is sufficient to support the amplification of a 3ps pulse. The 3ps pulse covers six rovibrational lines. The saturation energy in this case is assumed to be 200mJ/cm^2, which is six times the measured 35mJ/cm^2 for a single line operation. If 1% of the seed energy is coupled into the cavity, the Franz-Nodvik equation [14] predicts that 7.5nJ will be amplified in $\sim$7 round trips to $\sim$20mJ, using the measured small signal gain of 2.2%. By use of a GaAs Pockels

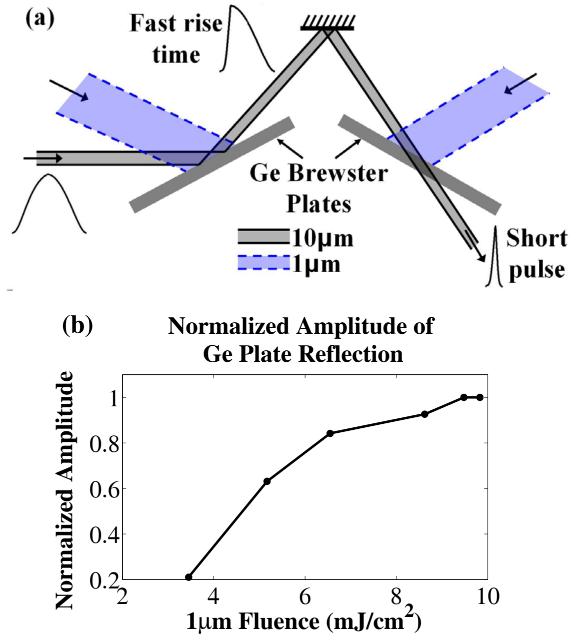

Figure 1: (Color) a) Diagram of two stage semiconductor slicing system. b) Normalized measured reflection of 10μm from a Ge brewster plate versus 1μm fluence.

cell, we anticipate to extract 80%, or 15mJ, of this energy for further amplification.

The final amplifier has a large aperture (20x35cm), e-beam controlled discharge with a single-pass length of 2.5m. It is operated at 3atm with a gas mix of 4:1 (CO_2:N_2) resulting in a single line bandwidth of 14GHz. Due to operation at a lower pressure, successful short pulse amplification relies on field broadening of these lines to fill the 55GHz gaps in the spectrum. Using the simulation code written by Platonenko [12], we have studied the effect of the input intensity on the final amplification. Fig.2 displays the pulse structure of a 3ps input pulse after a single pass (2.5m) amplification for three input laser intensities. The plot shows preservation of the original 3ps pulsewidth, as well as the formation of a pulse train. Incomplete broadening of the spectral lines leaves a 55GHz modulation across the gain spectrum which Fourier transforms to a pulse train in time domain. One can see that as the input intensity is increased from 1GW/cm^2 to 100GW/cm^2, the pulses trailing the main pulse decrease in amplitude which is evidence of stronger field broadening. Following these results, the intensity of our input pulse to the final amplifier will be kept $\geq$10GW/cm^2 to suppress the energy contained in the pulse train. Although stronger suppression is possible at higher intensities, it results in drastically smaller energy extraction, due to smaller spot size and stronger saturation, as well as the output fluence exceeding the damage threshold of 0.5J/cm^2 reported for a salt window [10].

Using this input intensity along with the measured small signal gain of 2.5% and calculated saturation energy of 100mJ/cm^2 [13], table 1 displays the results of the Franz-

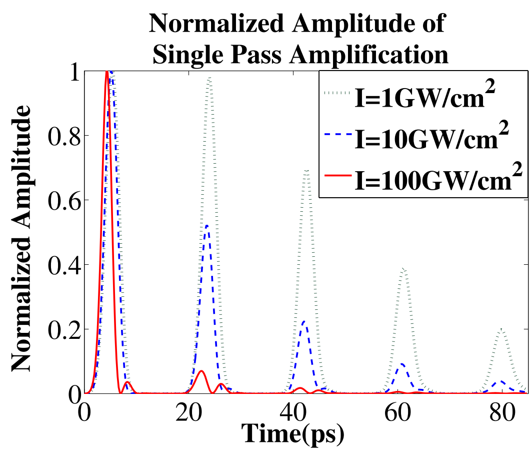

Figure 2: (Color) Normalized amplitude of a 3ps pulse after single pass (2.5m) amplification.

Nodvik predictions for 3 passes of amplification. For each pass, the the spot size is adjusted to keep the intensity at 10GW/cm^2. According to Fig.2, at this intensity, approximately 40% of the output energy is contained in the main pulse. This results in ∼30J contained in the leading 3ps pulse which can easily accomplish the goal of reaching an intensity of 10^{16}W/cm^2 and a_o=1. These pulses are certainly sufficient for the ionization of H_2 (10^{14}W/cm^2), but also allows for further study involving the acceleration of Helium ions: He^{1+} (1.5×10^{15}W/cm^2) and He^{2+} (10^{16}W/cm^2). If the full 30J is achieved, it will enable the use of pulses with powers up to 10TW and achieve a focused intensity of 1.6×10^{17}W/cm^2 and $a_o \sim 3$.

Table 1: 3-Pass Amplification

Pass	E_{in}	w_o	E_{out}
1^{st}	15mJ	4mm	260mJ
2^{nd}	260mJ	1.7cm	4.5J
3^{rd}	4.5J	7cm	78J

STATUS OF THE PROTON SOURCE EXPERIMENT

While the laser system is being upgraded, concurrent work has been completed in preparing the gas jet. The nozzle has an opening measuring 0.5mm x 1.2mm which produces a rectangular plume of gas in order to simulate a 'slab' with respect to the laser pulse of $2w_o = 140\mu$m. Plasma density interferometry has been used to characterized the gas jet at a range of gas pressures from 100psi to 600psi. A 40fs Ti:Sapphire laser pulse with 5mJ of energy was used to ionize a column of H_2 across the 500μm width of the nozzle at a height of 480μm above the tip. The gas jet was situated in an arm of a Mach-Zehnder interferometer which produced interference fringes when the H_2 gas was ionized. These fringes were then analyzed using an Abel inversion program producing a plasma density plot. Three such plots are shown in Fig. 3 which were taken at a gas pressure of 200psi at three positions transverse to the direction of laser propagation.

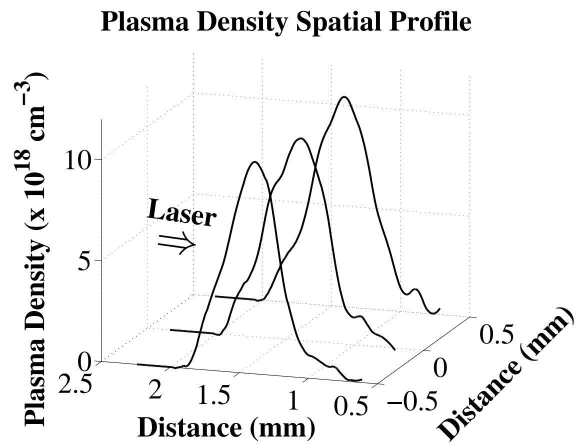

Figure 3: Spatial density profile of the laser produced plasma in a H_2 gas jet obtained via interferometry.

The average peak density is $1.25 \times 10^{19} \pm 2.5 \times 10^{18}$cm^{-3} and FWHM is $460 \pm 30\mu$m. Therefore, with respect to the spot size of the laser ($< 200\mu$m), the target is relatively flat ensuring normal incidence for the entire beam.

CONCLUSION

We described an ongoing project on CO_2 laser driven proton acceleration at the UCLA Neptune Laboratory. The installed H_2 gas jet provides a plasma source easily tunable around the plasma critical density of $\sim 10^{19}$cm^{-3}. The CO_2 laser MOPA system is being upgraded to produce 3ps 10μm pulses of TW power for driving the acceleration.

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