CO2 laser-plasma interaction provides a unique parameter space for particle acceleration in a gas jet plasma taking place at a critical plasma density $n_c \sim 10^{19}$ cm$^{-3}$ and even at higher densities ($3 \sim 10 \ n_c$) of 10$\mu$m radiation. Here we report the latest results of our study of electron acceleration in a wide range of plasma densities 1−10 $n_c$ using a multi-TW CO2 laser system at the UCLA Neptune Laboratory. To gain insight into plasma density profile evolution during ~120 ps long CO2 laser-plasma interaction, we used laser interferometry with two 1 ps, 532 nm probe pulses with variable delay of 5–120 ps. The knowledge of spatial distribution of accelerated electron beam transported through the overdense gas plasma is critically important for minimizing laser beam filamentation and for understanding influence of other laser-plasma instabilities. This should allow for optimization of CO2 laser driven shock wave acceleration of low-divergence monoenergetic ion beams [1].

**EXPERIMENTAL SETUP**

**Target Chamber**

The CO2 Master Oscillator Power Amplifier system having a multi-terawatt peak power is used in the experiment. Due to a modulated gain spectrum of the CO2 molecule, a ~3ps CO2 laser seed pulse evolves into a ~120ps long pulse train after amplification. Each individual pulse within the pulse train preserves the original pulse width and is separated from the adjacent pulse by ~18ps.

The experimental arrangement in a target chamber is shown in Fig. 1.

Figure 1: Experimental setup in the target chamber.

A 5” diameter CO2 laser beam with an energy of ~60J is coupled into the target chamber through an 8” NaCl window mounted on a 4° wedged flange. The back reflection of the beam from the salt window is combined with a red diode laser beam in a CS2 Kerr modulator. The red pulse modulated by the high intensity 10μm CO2 laser is analysed by a Hamamatsu streak camera (Model: C5680-21) for the temporal structure measurement of the CO2 pulse. The beam inside the chamber is focused in a 2mm diameter gas jet by an 8.5” F/3 off-axis parabolic mirror. Using an IR camera, we have characterized the spatial profile of the unamplified CO2 laser beam by scanning along the laser axis (Z-scan) which is shown in Fig. 2. The measured spot size is $w_o = 48\mu$m. Using this spot size and an estimate of the energy contained in the most intense of the 3ps pulses (~20%) in the train of pulses, we estimate that a peak $a_o$ of >1 can be achieved in these experiment. Here $a_o$ is the normalized vector divergence. A permanent magnetic dipole with ~600 Gauss magnetic field is placed before the LANEX phosphor screen to estimate the energy of particle beams.

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potential with a \( n_\parallel \) corresponding to \( 10^{16} \text{ W/cm}^2 \) for a CO\(_2\) laser.

Figure 2: Spot size measurement of 10\( \mu \)m CO\(_2\) laser beam.

The laser beam interacts with a pulsed supersonic gas jet which allows for the peak plasma density around 0.1 to 10 times of the critical density for the 10\( \mu \)m light (\( 10^{19} \text{ cm}^{-3} \)).

As shown in Fig. 1, a detector consisting of a 260\( \mu \)m LANEX phosphor screen (Left), 12.5\( \mu \)m Al foil (Middle) and 220\( \mu \)m Teflon (Right) layer is put 150mm away from the gas jet. The LANEX phosphor screen imaged by a COHU analog camera outside the target chamber is used to detect the forward directed electron beams with energy above 220keV. A permanent magnetic dipole (600 Gauss) capable of resolving energy in the range of 0.3-4 MeV is placed between the gas jet and the LANEX phosphor screen. A top COHU analog camera is installed to determine the focal position of the high power CO\(_2\) beam relative to the center of the gas jet. A 1ps, 532nm, green probe with energy of \( \sim 20 \mu \text{J} \) is delivered to the interaction point (IP) for the two-frame interferometry and schlieren diagnostics.

Two-Frame Interferometry and Schlieren Diagnostics

The two-frame polarization based interferometry and schlieren optical scheme is depicted in Fig. 3.

Figure 3: Schematic of the 1ps, 532nm two-frame interferometry and Schlieren diagnostics setup. Beam Splitter (BS), Delay Stage (DS), Beam Combiner (BC).

The 1ps, 532nm elliptically polarized probe beam enters the narrowband polarization cube and is separated into P (60%) and S (40%) components. This is a classical Michelson scheme in which an arbitrary delay can be introduced for the S polarized component. Then, each of them goes through a quarter wave plate twice and changes their polarization. A translational delay stage of the S probing arm is used to control the temporal delay relative to the P arm. The adjustable temporal range is 5–120ps with the P probe arriving at the IP earlier. After switching the polarization, P and S probes follow the same beam path and enter into the Mach-Zehnder interferometry system. Another narrow band polarization cube is placed behind BC to separate the polarized beams into two orthogonal directions. The imaging lens transfers the image plane of the plasma to the two CCD cameras. The measured spatial resolution of interferograms is \( \sim 20 \mu \text{m} \).

In addition to the interferometry, part of the beam probing the plasma is reflected off BC for a Schlieren diagnostic. The reflected beam contains P and S components and we use another polarization cube to select P component for the Schlieren image. A dark field schlieren technique [2] is used to analyse the plasma density gradient. A \( \sim 250 \mu \text{m} \) diameter ink dot deposited on a 2” transparent plastic disc is used as a beam stopper. The green probe passing through the plasma without refraction is attenuated by the dot by a factor of \( 10^5 \). The measured resolution of the schlieren images is \( \sim 40 \mu \text{m} \).

EXPERIMENTAL RESULTS

At the Neptune laboratory, the 10\( \mu \)m short pulse and the 532nm probe pulse are both produced using the same 1\( \mu \)m pulse [3], so inherently they are deterministically synchronized with each other. However, due to the different transport length, they arrive at the IP at different times and need to be temporally re-synchronized with a picosecond accuracy. Also as mentioned earlier, our structured CO\(_2\) pulse train contains multiple \( \sim 3 \) picosecond micro-pulses separated by \( \sim 20 \)ps. We are interested in observing the interaction between the overdense plasma and different micropulses in the pulse train and to learn how the plasma density profile will evolve temporally. To synchronize CO\(_2\) laser pulse envelope and green probe with better than 20ps accuracy, a cross-correlation measurement in Si was used [4]. The probe timing of P arm is adjusted such that the probe pulse arrives approximately at the peak of the CO\(_2\) pulse train. And the relative delay of the S arm can be changed using a delay stage in order to cover a chosen micro-pulse that arrives at a later time.

One of the most important mechanisms in laser overdense plasma interaction is hole boring or pushing of the density steepened plasma layer by radiation pressure of the laser field. Two frame interferometry allows for accurate measurement of the hole boring speed. For example, for interferogram shown in Fig. 4, we can extract this information by comparing how the overdense plasma layer is pushed by the radiation pressure at two different times.
For this shot our CO$_2$ laser beam is focused into a helium gas jet target and the laser intensity is above the ionization threshold of He$^{2+}$ ($\sim 8.5 \times 10^{15}$ W/cm$^2$). According to our neutral density calibration data of the gas jet, a backpressure of 1000psi corresponds to $\sim 6n_c$ for a fully ionized He gas. Analysis of two interferograms of P and S arms (S is 46ps later) reveals that the pushed layer is moving forward with a hole boring velocity of $0.0037c$ ($c$ is the speed of light).

Using the formula $v_h = \frac{n_{cr} Z m n_{pe}^{1/2}}{\lambda_0}$ [5], where $v_h$ is the hole boring velocity, $n_{cr}$ the critical density for 10µm light, $n_{pe}$ the plasma density and $Z$ is the charge state of the ionized atoms, one can extract the laser intensity in the hole boring process which is $1.5 \times 10^{16}$ W/cm$^2$. However, this formula assumes a constant radiation pressure and not directly applicable for the case of CO$_2$ laser 3ps pulses separated by 18ps. Thus, the intensity $1.5 \times 10^{16}$ W/cm$^2$ corresponding to the measured $v_h$ is a lower estimate of the laser intensity in the experiment.

Another shot, shown in Fig. 5, corresponds to the case when neutral density of the gas jet was reduced. We observed a nicely formed plasma channel. Analysis of the fringe shift in the interferogram gives us the plasma density in the channel of P probe time equal to $1 \times 10^{18}$ cm$^{-3}$ and S probe equal to $5 \times 10^{17}$ cm$^{-3}$, which indicates a drop in plasma density over 46ps delay. Schlieren image in Fig. 5(c) shows a piled up plasma upstream of the plasma channel.

For this shot, a well-confined, beam-typed signal was detected on the LANEX screen with a divergence angle of $2^\circ$. Currently, we are studying the nature and energy of this forward directed beam.

REFERENCES