# DEVELOPMENT OF A HIGH-REPETITION RATE TW $CO_2$ LASER DRIVER FOR A COMPACT, VARIABLE SPECIES ION SOURCE

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*Abstract*

$CO_2$ laser-driven ion acceleration has been used to generate monoenergetic, MeV proton beams from a gas jet plasma. Use of a gas jet is advantageous because it offers interactions at a density around the critical plasma density for 10 μm pulses ($10^{19}$ $cm^{-3}$) and can be run at a repetition rate of 1-100 Hz. This opens the possibility to create a variable species ion source easily switchable from protons to light ions (*e.g.* He, N and Ne). A TW class high repetition rate $CO_2$ laser driver is required for implementing such a source. At the UCLA Neptune Laboratory we have built a 1 Hz $CO_2$ laser system and demonstrated the amplification of 20 GW, 3 ps laser pulses. However, peak powers on the order of 0.2-1 TW are required for producing ~ MeV proton beams. Here we report progress on an ongoing project in which the peak power of our laser system will be increased by nonlinear chirping and broadening followed by pulse compression. We also discuss a possible strategy for generating 300 mJ, 300 fs $CO_2$ laser pulses for driving a 1 – 10 Hz laboratory ion source.

## INTRODUCTION

There are applications in material science, radiation biology and medical physics [1] that would benefit from a MeV class, multiple species ion accelerator. The cost of such a machine, if built using conventional accelerator technology, is prohibitively expensive for most universities and hospitals. Laser driven ion acceleration (LDIA) may be one avenue for reducing this cost, either as a stand-alone accelerator or as an injector for a conventional accelerator.

Recent experiments have demonstrated monoenergetic, MeV ion acceleration from over-dense ($\omega_{plasma} \geq \omega_{Laser}$) laser plasma interactions (LPI) [2]. High power $CO_2$ lasers are an attractive candidate for LDIA because, at a wavelength of 10 μm, the critical plasma density can be achieved using a gas jet or cell. In contrast, the majority of high power lasers operate at wavelengths from 0.8 – 1 μm and must use solid targets to study over-dense LPI. Due to the potential ease in targetry, 10 μm drivers are the most technological option for a multi-species, laser driven ion accelerator.

$CO_2$ LDIA studies have been limited to single shot experiments even though optimization of the laser-plasma interaction may only be possible at a high repetition rate. Although gas jet technology can be scaled up to 100 Hz, experiments have suffered due to limitations in the repetition rate of the driver. At the UCLA Neptune Laboratory we have recently developed a 20 GW, 3 ps $CO_2$ laser system which operates at 1 Hz [3]. Peak power on the order of 0.2 TW is required for acceleration of ~ 3 MeV protons from a $H_2$ plasma. In this paper we investigate a method to increase the peak power of our system by using nonlinear chirping and broadening followed by compression. Further we propose a path to a 300 mJ, 300 fs $CO_2$ laser to be used as a 1 – 10 Hz driver for a compact, multi-species ion source.

## STATUS OF THE 1 HZ, PICOSECOND $CO_2$ LASER SYSTEM

$CO_2$ lasers have some technological advantages that cannot be matched by solid state laser systems. The gas medium can withstand intensities up to the ionization threshold, $\geq 10^{12}\frac{W}{cm^2}$, which allows for direct amplification of short pulses. Further, gas discharge technology can be scaled in repetition rate and provides high wall plug efficiency. Despite these advantages, high peak power amplification in $CO_2$ is difficult due to the relatively narrow bandwidth present in gaseous media. Gas lasers typically provide a bandwidth of 3.5 GHz/atm such that, at 1 atm of pressure, a $CO_2$ laser can only produce pulse lengths greater than 1 ns. Unfortunately, pulse lengths on the order of picoseconds or less are necessary to reach the relativistic intensities required for LDIA.

At the UCLA Neptune Laboratory we achieve broad band $CO_2$ laser amplification by relying on two broadening mechanisms: pressure and field broadening. Figure (1) shows simulated gain spectrums of the $CO_2$ medium at 1, 10 and 25 atm of pressure. At 1 atm of pressure the gain spectrum consists of a family of 3.5 GHz, rovibrational lines.

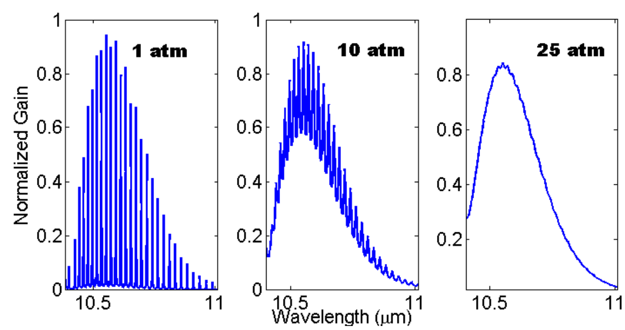


Figure 1: Simulations of the $CO_2$ gain medium at 1, 10 and 25 atm of pressure for the 10P branch.

At high pressures the collisional time becomes comparable to the radiative transition time which results in line broadening. At 25 atm of pressure the gain spectrum is a continuum across the entire 1.2 THz branch. In practice modules with 10 atm of pressure are used as it is difficult to obtain stable discharge at pressures greater than this. The presence of residual modulation in the gain




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spectrum at 10 atm results in the amplification of a pulse train as depicted in figure 2. The resulting pulse train consists of 5 – 7, 3 ps pulses separated by 18 ps.

After the pulse reaches intensities on the order of $GW/cm^2$ the lasing transition can be broadened by the field of the pulse itself. This broadening manifests in a way similar to the ac Stark effect and can be estimated by $\Delta\nu_{Field} \approx \mu\sqrt{I}$ where $\mu$ is the dipole moment in Debye and $I$ is the peak intensity of the pulse. For $CO_2$ $\mu = 0.0275$ such that, at intensities of $10\frac{GW}{cm^2}$, a 1 atm amplifier has the bandwidth of a 10 atm machine [3]. The total broadening is the sum of the pressure and field dependent terms, $\Delta\nu_{Total} = \Delta\nu_{Pressure} + \Delta\nu_{Field}$.

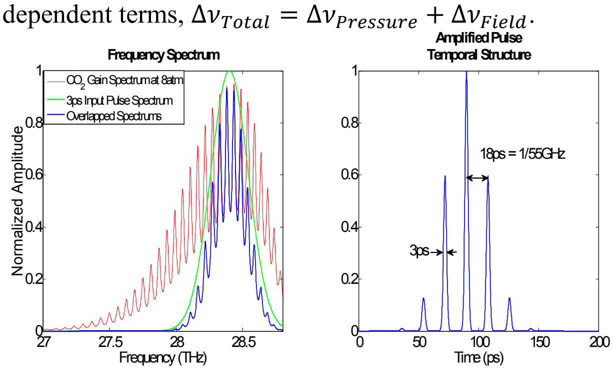


Figure 2: Simulations showing the production of a ps pulse train after amplification of a single ps pulse in a 10 atm $CO_2$ laser.

Figure 3 is a block diagram of the Neptune Laboratory's $CO_2$ master-oscillator power-amplifier chain where amplification is realized in two stages. In the first stage the pulse is amplified from nJ to mJ in two 8 atm $CO_2$ lasers where the pressure sustains the bandwidth for ps pulse amplification. The first module is used as a regenerative amplifier while the second module is used as double pass booster. In the second stage the seed is sent for final amplification in a 1 meter, 1 atm $CO_2$ laser where the field from the pulse sustains the bandwidth for final amplification.

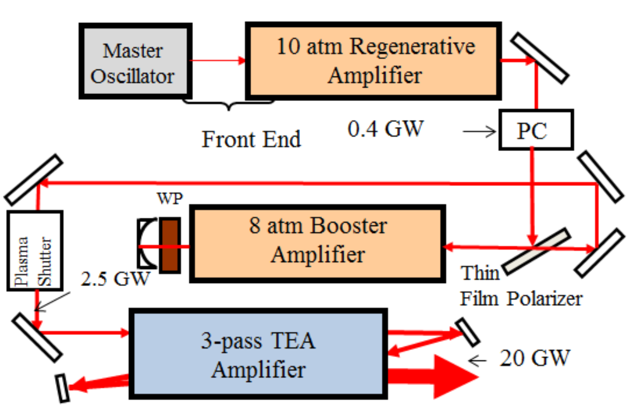


Figure 3: Block diagram of the Neptune Laboratory's high repetition rate system. The orange and blue blocks refer to amplifiers which use pressure and field broadening to sustain ps bandwidth, respectively.

Figure 4 is a plot of the temporal structure of our output pulse train as measured by a streak camera. As simulations predict, the pulse train consists of 3 ps pulses separated by 18 ps, a time scale related to the 55 GHz modulation in the gain spectrum.

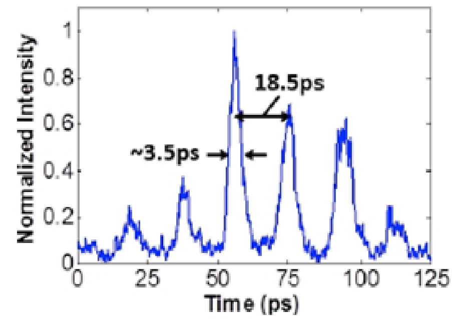


Figure 4: Temporal profile of the ps pulse train

As reported in [3] we extract 200 mJ out of our final amplifier which results in a peak power of 20 GW for the most intense pulse in the train. The amount of extracted energy is limited by saturation and could be increased if the 1 atm final amplifier was replaced by a larger aperture, 2 – 3 atm TE $CO_2$ module.

## NONLINEAR SPECTRAL BROADENING IN A NOBLE GAS FILLED HOLLOW GLASS WAVEGUIDE

A peak power beyond one defined by the $CO_2$ bandwidth can be obtained via self-phase modulation in a nonlinear optical medium. Nonlinear spectral broadening and subsequent compression of guided waves is a technique which has been successful in the near-IR but has not been explored at 10 μm. Hollow glass waveguides (HGW) which are coated with Ag/AgI are commercially available and have been used in our laboratory to guide GW, 10 μm pulses with a throughput of 95% in the air [4].

Figure 5 illustrates our scheme to use a Xe filled HGW to broaden and chirp our pulses through self-phase modulation. After the HGW the pulses will be compressed via propagation through NaCl, a material with negative group velocity dispersion at 10 μm. The plots of figure 5 depict simulated time and frequency domain representations of our pulse train before and after the pulse compressor.

We have modelled this process by numerically solving the nonlinear Schrödinger equation [5] for our pulse parameters. We have assumed a waveguide radius of 500 μm which corresponds to a peak intensity of 6 $TW/cm^2$ when the beam is coupled into the $EH_{11}$ mode of the waveguide. The pulse is broadened by a factor of 5 in 200 cm of Xe gas. The length of NaCl to compress the output pulse train was approximately 35 cm which results in 100 GW, 650 fs pulses on the output of the Brewster angled salt plate. Currently the set-up for pulse compression is being built.

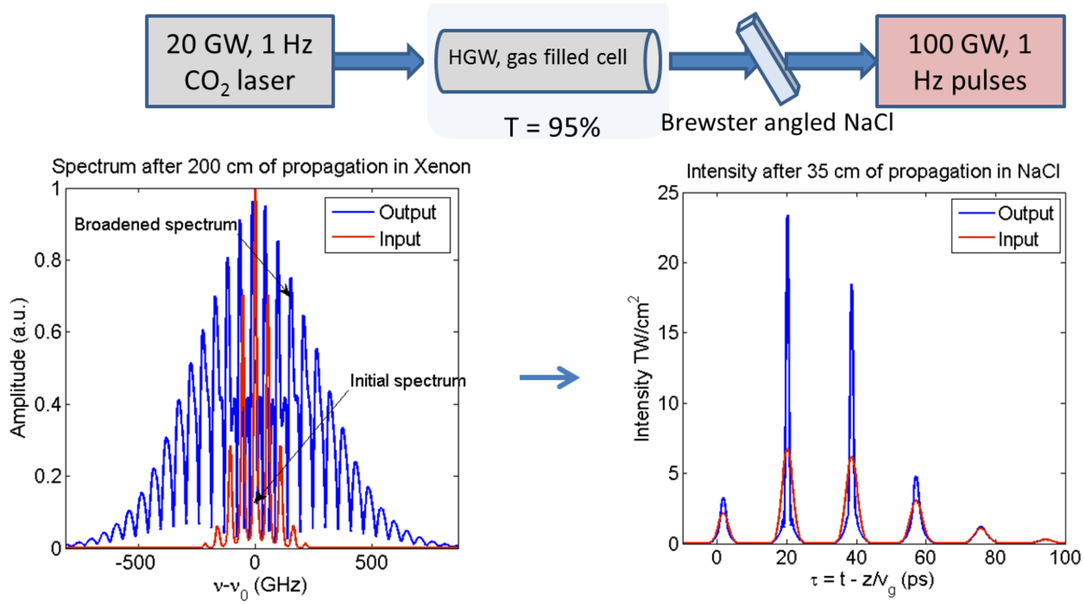


Figure 5: Top: Proposed set-up to use self-phase modulation followed by compression in NaCl to produce 100 GW $CO_2$ laser pulses. Bottom: Simulated frequency and time domain representations of our pulse train before and after the pulse compressor.

Based on this technique we envision the development of a 1 TW, 1-10 Hz $CO_2$ laser system by using the strategy described here. In order to extract the energy required to produce a TW class driver we must first replace the 1 atm final amplifier with a 100 cm length, 3 atm $CO_2$ laser. With this final amplifier we can extract 3 J of energy which can be sent through the same nonlinear pulse compressor of figure (5) to produce 300 fs, 300 mJ pulses.

## CONCLUSION

We have presented the status of an on-going project to develop a 100 GW $CO_2$ laser driver for a variable species ion source at the UCLA Neptune Laboratory. If nonlinear broadening in 200 cm of a noble gas filled HGW followed by pulse compression is successful then we will scale the interaction to generate >0.1 TW $CO_2$ laser pulses. This power will be sufficient to study $CO_2$ LDIA with a gas jet target. The capability to study LDIA at a high repetition rate is critical for understanding and optimizing the laser plasma interactions responsible for ion acceleration. Such a system would be an ideal driver for a multi-species, MeV class ion accelerator.

## ACKNOWLEDGMENT

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