DEVELOPMENT OF PICOSECOND CO_2 LASER DRIVER FOR AN MEV ION SOURCE

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Abstract

Laser-Driven Ion Acceleration in thin foils has demonstrated high-charge, low-emittance MeV ion beams with a picosecond duration. Such high-brightness beams are very attractive for a compact ion source or an injector for RF accelerators. However in the case of foils, scaling of the pulse repetition rate and improving shot-to-shot reproducibility is a serious challenge. CO_2 laser-plasma interactions provide a possibility for using a debris free gas jet for target normal sheath acceleration of ions. Gas jets have the advantage of precise density control around the critical plasma density for 10 μm pulses (10^{19} cm^{-3}) and can be run at 1-10 Hz. The master oscillator–power amplifier CO_2 laser system at the UCLA Neptune Laboratory is being upgraded to generate 1 J, 3 ps pulses at 1Hz. For this purpose, a new 8 atm CO_2 module is used to amplify a picosecond pulse to ~10 GW level. Final amplification is realized in a 1-m long TEA CO_2 amplifier, for which the field broadening mechanism provides the bandwidth necessary for short pulses. Modeling of the pulse amplification shows that ~0.3 TW power is achievable that should be sufficient for producing 1-3 MeV H^+ protons from the gas plasma.

INTRODUCTION

Laser-Driven Ion Acceleration (LDIA) in thin foils has demonstrated high-charge, low-emittance MeV ion beams with a picosecond duration [1]. However, a solid foil based proton source has drawbacks limiting its practical use, since it susceptible to any prepulse, which leads to plasma formation at the target surface before the arrival of the main pulse, produces debris and its repetition rate is limited. If these problems can be overcome and ions can be accelerated to 1-10 MeV/u at a high-repetition rate, such a laser-driven source of ions could find application as a picosecond injector for a conventional accelerator or a compact ion source for high-energy-density physics and material science.

An alternative method of obtaining laser accelerated ions is by using a gaseous target. An ionized gas is a clean source of protons or ions from other gases. A supersonic gas jet can provide neutral gas densities in the range of 10^{18}-10^{20} cm^{-3} with homogeneous density distribution in a 50-2000 μm neutral gas slab and can be easily operated at 1-10 Hz. For a 10 μm laser pulse, the gas jet target with a peak plasma density greater than the critical density 10^{19} cm^{-3} can be used for ion acceleration. Compared to solid foils, using a gas jet is potentially very attractive as it produces no debris and can be run at a high-repetition rate and the density of the plasma can be changed easily in a well controllable manner.

Thus 10 μm LDIA in a gas jet could represent a promising alternative to using solid foils to obtain a high-energy proton beam. To achieve relativistic laser fields before the deposited energy causes the gas target expansion, a high-power picosecond CO_2 laser is needed. Recently, at ATF BNL a picosecond CO_2 pulses were applied for generation of ~1MeV protons in the H_2 jas jet [2]. At the UCLA Neptune Laboratory a TW class (100 J, 100 ps) CO_2 laser system has been operational for many years [3] and a 3 ps long pulse has recently been amplified to to greater than 10 TW with a normalized field strength of $a_0 \geq 1$ in a focused beam [4]. In first LDIA experiments in a gas jet using these multiterawatt CO_2 laser pulses, collimated forward proton beams were generated with a kinetic energy of particles reaching 25 MeV [5]. However, single-shot nature of these experiments [1,5] hinders optimization of the laser-plasma interactions and, therefore progress towards a laser driven ion source. Here we report on the high-repetition rate picosecond CO_2 laser driver which is being built for LDIA experiments.

ION SOURCE CONCEPTUAL DESIGN

A conceptual design of a 1 Hz CO_2 laser driven ion accelerator in a gas jet is shown in Fig.1. A 3 ps long intense 10 μm pulse ionizes the H_2 gas and accelerates protons at a peak plasma density around n_c. Laser-plasma interactions result in ~MeV proton beam with an energy spread of +/- 5% [1,5] which can be focused by a pulsed solenoid [6]. The focused beam will be coupled into a RF cavity synchronized with the CO_2 laser in order to rotate the beam in a longitudinal phase space and decrease the energy spread to better than 1% similar to A.Noda et al [7]. The main goal of the study will be optimization of 1 Hz proton/ion source which potentially can be used as a high-brightness injector for RF based accelerators or a picosecond beam source for proton radiography.

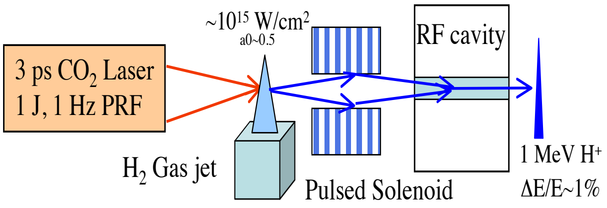

Figure 1: A schematic of the CO_2 laser driven monoenergetic proton source.

PICOSECOND CO_2 LASERS

Producing a picosecond pulse with a CO_2 laser is difficult because of the relatively narrow bandwidth of the carbon dioxide molecule. The gain spectrum of the CO_2 molecule centered around the 10.6 µm P-branch spans ~1.2THz consisting of discrete rotational lines separated by 55GHz. When the bandwidth of these lines is sufficiently broadened, they overlap filling the gaps in the spectrum which results in a quasi-continuous bandwidth across the branch suitable for amplification of >1 ps pulses. Several techniques can be used for generating low-power 10 µm pulses on a time scale of 1-3 ps. Such pulses can be amplified in high-pressure (≥ 10 atm) carbon dioxide lasers, when the collisionally broadened linewidth is approximately 30 GHz. Unfortunately, technically it is extremely difficult to obtain uniform glow discharge in a large aperture (>5 cm^2) module at a high pressure (> 5 atm). As a result output of the multiatmosphere CO_2 amplifier is limited because of rather small volume. Obtaining stable discharges in high-pressure gas at high pulse repetition frequency imposes further limitation on the gain volume.

An alternative approach is to use power of the laser field itself, instead of pressure broadening, to provide the necessary bandwidth for high-power amplifiers [4]. Here, the resonant interaction of the strong electric field of the laser pulse with the CO_2 molecule (similar to the ac Stark effect) causes a transient increase in the bandwidth. The effect of field broadening on the rotational linewidth can be estimated by:

$$\Delta\nu = \Delta\nu_{pressure} + 2\left(6.91\bullet10^{6}\mu\sqrt{I}\right) \qquad (1)$$

where $\Delta\nu_{pressure}$ is the collisional linewidth, µ is the dipole moment in Debye, and I is the laser intensity in W/cm^2. For the 10.6 transition, calculations using Eq. (1) show that at intensity of 5 GW/cm^2 even for a 1 atm amplifier, the resultant linewidth of 37 MHz is comparable to that of the 10 atm amplifier. Therefore, once a sufficient power is generated in a pressure broadened CO_2 module, it can be further amplified in a field broadened medium (coherent amplification regime) ultimately in a TEA module. Note that the latter technology is very well developed and kHz CO_2 lasers are commercially available.

However, regardless of line broadening mechanism insufficient broadening of these lines results in a residual modulation of the gain spectrum at 55GHz. When a short 3ps pulse propagates in an amplifying medium with a periodically modulated gain spectrum, some frequencies in the pulse bandwidth will not be amplified efficiently and the Fourier transform for such a case results in a pulse train with a pulse separation equal to 1/55GHz, or 18ps. In this case the individual pulse width is limited by the bandwidth of the branch (1.2 THz) and the length of the pulse train envelope is limited by the bandwidth of the rovibrational line.

1 HZ PICOSECOND CO_2 LASER

In Fig. 2 we present a scheme where the existing at the UCLA Neptune Laboratory Master Oscillator –Power Amplifier (MOPA) CO_2 laser chain is complemented with two new 1 Hz CO_2 laser discharge modules (indicated by plum color) for amplification of the 3 ps pulse to 1 J level. This should provide an intensity of up to $2x10^{15}$ W/cm^2 in the focused beam (spot size ~40 µm).

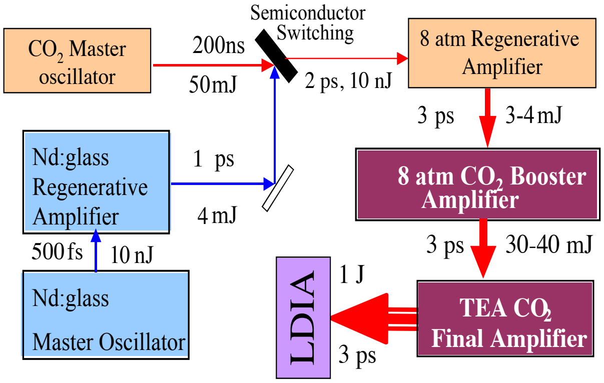

Figure 2: Scheme of a 0.3 TW, 1Hz CO_2 laser system.

First, a ~4 mJ output pulse of the regenerative amplifier is sent to an 8 atm TE CO_2 Booster Amplifier (HP3, SDI Lasers), in which a 40 mJ pulse is extracted after two passes. Reaching GW level of power in a high-pressure CO_2 module allows for further coherent amplification. This is realized in a 1-m long TEA CO_2 laser amplifier (LaserMark 960, Lightmachinery Inc.). It has a relatively large aperture 25x25 mm^2 suitable for energy extraction on the Joule level. If the first step of amplification does not cause any concern from the laser pulse dynamics point of view, the second stage is subjected to very high laser fields and has to be designed carefully.

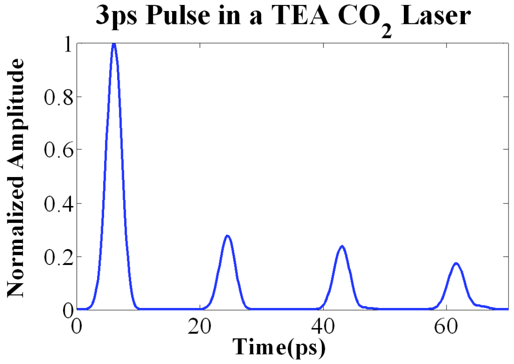

Figure 3: Simulated temporal pulse profile for a single 3 ps pulse amplified in a TEA CO_2 laser at 20 GW/cm^2 input laser intensity.

For modeling of the TEA CO_2 Final Amplifier, we choose 20 GW/cm^2 input laser field intensity. A computer code developed by Dr. V. Platonenko (MSU) [8] was used in analysis. The code calculates electrical fields for each of the frequency components involved in the amplification process and the CO_2 active medium is described as a manifold of rovibrational levels. From results of the simulations presented in Fig. 3, it is clear that coherent amplification provides preservation of the leading 3 ps pulse even at 1 atm. The energy is extracted in a train of 3 ps pulses separated by 18.5 ps. Note that picosecond pulse train can be beneficial for LDIA in a gas jet [5].

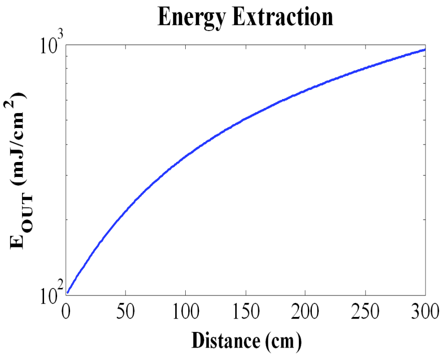

Figure 4: Calculated energy extraction from a TEA CO_2 laser versus the amplification length for a small-signal gain of 2%/cm.

The extracted energy from the TEA module calculated using Franz-Nodvik equation is shown in Fig. 4. Here after 3 meters of amplification, an output energy reaches 1 J/cm^2. However, the damage threshold of a NaCl window (~0.7 J/cm^2) is an important constraint in designing the final amplifier. Thus three passes through a 1-m long TEA CO_2 amplifier is necessary for reaching the 1J level. Moreover, the last pass should have a beam radius larger than 8 mm (area of 2 cm^2) keeping the laser fluence below the damage threshold.

STATUS OF THE SYSTEM

At present all gain modules are delivered to UCLA. The high-pressure booster amplifier is installed, characterized and used for the IFEL experiments [9]. The measured gain for the 3 ps long pulse in a 1:1:12 CO_2:N_2:He laser mix (8 atm) reaches 3%/cm. At present the optical design for multi-pass scheme is completed and first proof-of-principle experiments on coherent amplification of 3 ps pulses in a TEA CO_2 amplifier are planned for this year.

ACKNOWELEDGMENTS

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