Optical pumped ultra-short pulse CO_2 lasers as drivers of laser-plasma accelerators and other applications

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ABSTRACT

Optically pumped CO_2 lasers can operate with high efficiency, high repetition rate and large bandwidths, suitable for producing ultra-short pulses at terawatts to petawatts, in contrast to conventional discharge-pumped CO_2 lasers, which are restricted by the requirements of discharge dynamics in high-pressure gas. We show how an optically pumped CO_2 laser can be realised and we consider its application in laser-driven acceleration. There is potential to replace conventional transversely excited atmospheric CO_2 lasers with diode-pumped solid-state lasers as a pump laser for a high-pressure CO_2 gain medium, making it suitable for amplifying ultra-short pulses. We show that by driving a laser plasma wakefield accelerator with an ultra-short pulse CO_2 laser, a very high charge, high average current, high energy accelerator can be constructed. This could have a major impact on the application of these novel accelerators and radiation sources based on them.

CO_2 lasers, laser wakefield accelerators, optically pumped lasers, ultra-short pulse CO_2 laser, EUV photolithography, diode pumped solid state lasers

1. INTRODUCTION

High power lasers are driving a revolution in the development of radiation sources and particle accelerators. They are very versatile and have applications in academia, industry and the environment. Since the advent of the laser, the maximum peak power possible has increased inexorably, growing an order of magnitude every decade. Solid-state lasers are now used in almost all manufacturing applications, but the carbon dioxide (CO_2) laser remains the mainstay driver of plasma sources used in the current generation of EUV photolithography for microfabrication of very large scale integrated circuits[1]. Current CO_2 laser technology is based on transversely excited atmospheric (TEA) or radio frequency (RF) discharges, which have well-established performance ceilings and maintenance requirements. To reach very high powers and ultra-short pulse (USP) durations (≤1 ps), CO_2 lasers have become very large and operate at low rep rates. They also require high pressures to achieve bandwidths suitable for amplifying USPs, which is a challenge if high energy and high repetition rates are required simultaneously. Commercial EUV photolithography demands more than 30 kW and therefore CO_2 lasers of multi-10s of mJ (~ 0.2-0.5 J), 10s ns duration, 50-100 kHz would be required to drive laser driven plasma (LPP) sources. High-pressure, discharge pumped CO_2 systems have constraints on gas mix species and composition[2], which limits their gain bandwidths and effectively precludes amplification of sub-ps pulses. Because of the requirement of high gas pressures, their repetition rates are limited, mainly by residual acoustic waves that cause discharge instabilities. Small signal gain in the range of 5-10%/cm, together with high volumetric extraction in high pressure mixtures, are essential for both USP and LPP-EUV CO_2 master oscillator power amplifier (MOPA) designs, which is not feasible in discharge pumped systems[3].

There has been a huge growth in interest in laser-driven plasma wakefield accelerators[4] (LWFAs) since its first demonstration in 2004[5]. It has become clear that the laser-driven accelerator is a paradigm shifting accelerator technology[6,7]; accelerators can now be reduced in size by 3-4 orders of magnitude, by replacing RF cavities with plasma structures, where electric fields are produced by plasma wakes or charge separation. These ultra-compact accelerators are also ultra-compact radiation sources[8-10], because their accelerator structures are strong emitters of electromagnetic radiation, which occurs over a wide frequency range, from meV (THz frequencies)[11,12] to MeV (gamma ray energies)[9]. Furthermore, non-injected electrons emitted from the LWFA can lead to 10s of nC, 1-2 MeV electron bunches emitted in a wide conical-shaped beam, which can be used in imaging, damage and materials processing studies[12,13]. Current LWFAs are based on TW peak power Ti:sapphire lasers, which have relatively low efficiencies and currently operate at repetition rates limited to several Hz.

2. USP CO$_2$ LASERS DRIVEN BY DIODE PUMPED SOLID-STATE LASERS

We investigate the feasibility of developing optically pumped, USP CO$_2$ lasers as drivers for LWFAs and applications such as photolithography and remote sensing. We show that optical pumping eliminates the need for multi-pass preamps (as used currently in LPP-EUV MOPA's and picosecond systems) and allows power amps (PAs) that readily saturate because of their high small signal gain. A 100 kHz, 2.5 kW, 4-element oscillator, comprising 4 optically pumped ring oscillators, each with a gain length of ~ 6 cm, may be used as a front-end for current compact LPP-EUV MOPA drivers. Injection seeds select low-pressure CO$_2$ lines, which are spectrally combined and therefore eliminates the need for pre-saturated multi-pass systems. They replace the current oscillator, two preamps and half of the first PA that are often found in current systems. Subsequent low-pressure PAs operate at saturation, which results and in a lower overall system gain-length product and enables further power scaling, while avoiding instabilities. Optical pumping enhances the active volume extraction by 3-4 orders of magnitude, and use of PAs admits further scaling. The proposed CO$_2$ laser is pumped by diode pumped solid state (DPSS) lasers, using the two possible pumping schemes shown in Fig. 1.

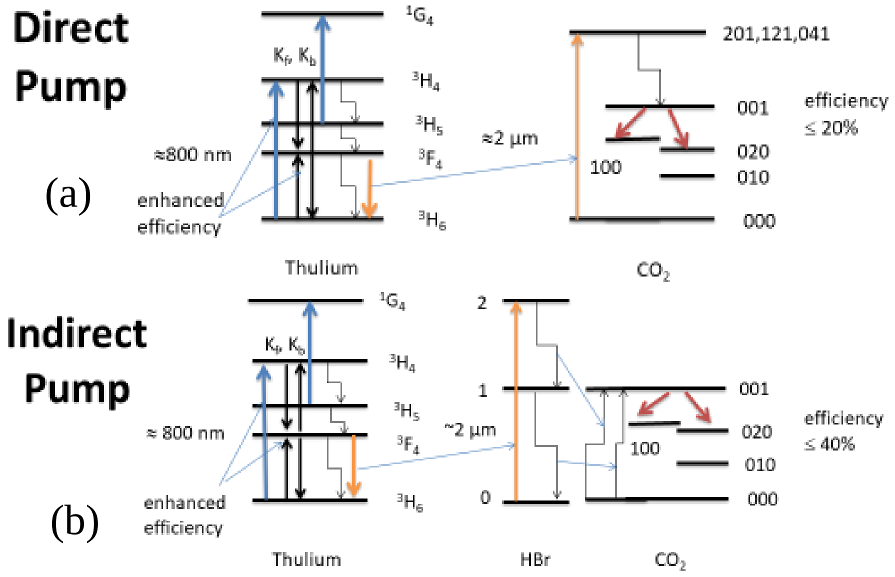

Figure 1. Pumping schemes: direct pumping and indirect pumping

Increasing the CO$_2$ partial pressure for a given gain limits vibrational temperature and molecular dissociation (discharge pumped systems require reduced partial pressures). Optical pumping lowers molecular dissociation to acceptable rates, and "engineering" of the gas mix increases the amplifier bandwidth to support sub-ps USPs. The enhanced gain and reduced number of passes mitigates B integral growth. Fig. 2(a) shows layout examples of a tandem pump arrangement.

At raised pressure operation, the pump bands are broad: 1-2 THz for a single isotopologue, and up to ~8 THz for multi-isotopologue mixes. The DPSS to pump band matching is robust and has an ideal spectral match to the pump bands. Fig. 2(b) shows a schematic of a DPSS-CO$_2$ high-pressure amplifier suitable for USPs. Current discharge pumped USP CO$_2$ systems require a high-pressure regenerative oscillator and a semiconductor switch, or an OPA, followed by several multi-pass preamps and PA. In contrast, an optically-pumped system requires an OPA, as shown in Fig. 2(b), which produces a seed that is amplified to ≈30 mJ over 4 passes in an unsaturated preamp with ~ 50 cm gain length, followed by a saturated PA. Because of the design flexibility afforded by optical pumping, the gain region geometry can be structured for the desired performance, while maintaining efficiency, high repetition rate (multi kHz), high pulse energies and USP bandwidth.

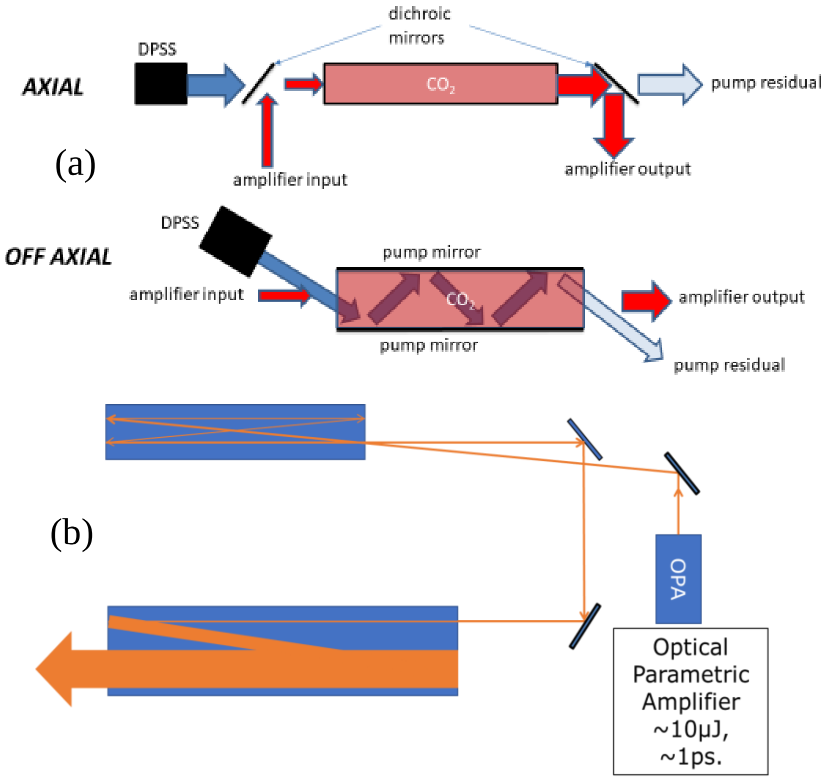

Figure 2. (a) Schematic of pumping schemes, (b) MOPA system: OPA, preamplifier & final amplifier**.**

3. CO_2 LASERS DRIVEN LASER PLASMA WAKEFIELD ACCELERATORS

The ponderomotive force responsible for producing charge separation in laser-plasma accelerators is proportional to $I\lambda^2$, where I is the laser intensity and λ the wavelength. Therefore, longer wavelength lasers are more effective in driving the plasma than shorter wavelength lasers. Acceleration using a 10.6 µm (CO_2) laser requires an intensity that is a factor of 175 lower than for a 800 nm (Ti:sapphire) laser, for the same ponderomotive force. A 1 J, 30 fs, 800 nm laser produces 10 pC bunches of 150 MeV electrons for a plasma density of $\approx 10^{19}$ cm^{-3}. To achieve similar electron energies using a 10.6

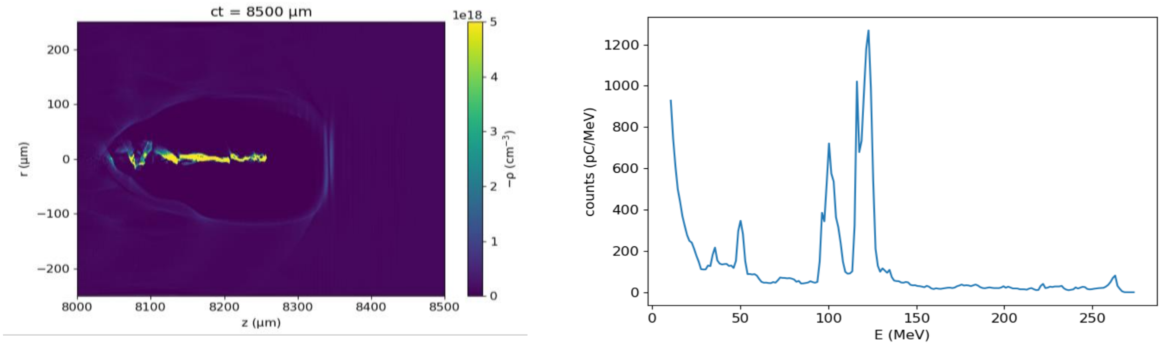

Figure 3. FBPIC simulations using a preformed uniform plasma showing bubble formation and electron energy spectrum. Laser wavelength: 10 µm, pulse duration (FWHM): 300 fs, energy: 11 J, beam waist: 100 µm, a_0: 4, plasma density: 10^{17} cm^{-3}, propagation length: 8.5 mm, charge in peak is 10 nC.

μm CO_2 laser driver requires reduced plasma density because of the lower group velocity at 10.6 μm, and the requirement for a longer and wider pulse for matched driving. Similar energies are possible using a CO_2 laser with a lower density plasma and a longer interaction length. This has been verified by performing quasi-3D particle-in-cell (PIC) simulations with the code FBPIC[14]. A laser with wavelength of 10 μm, 300 fs (FWHM) pulse duration focused down to a spot size (at $1/e^2$ intensity) of $w_0 = 100$ μm interacts with a uniform pre-formed plasma. The laser energy and plasma density are varied to investigate the effect on the accelerator performance. Simulations presented in Figure 3 show that very high charge (10 nC level) electron bunches of an energy around 130 MeV can be produced by a suitably matched 11 J, CO_2 laser interacting with a plasma with a density of 10^{17} cm^{-3}.

A 1 kHz laser would produce a beam with an average current of 10 μA, while at 100 kHz it would produce 1 mA.

The energy of the LWFA can be increased by using a higher laser energy. For a 300 fs (FWHM) pulse duration, 25 J energy, 10 μm laser pulse focused to a spot size (at $1/e^2$ intensity) of $w_0 = 100$ μm we can obtain a normalised laser vector potential of $a_0 = eA/m_e c = 6$, where A is the laser vector potential, m_e the electron mass, e the electron charge and c the speed of light. Relativistic self-guiding ensures that the laser intensity remains high for a propagation length of 15 mm in

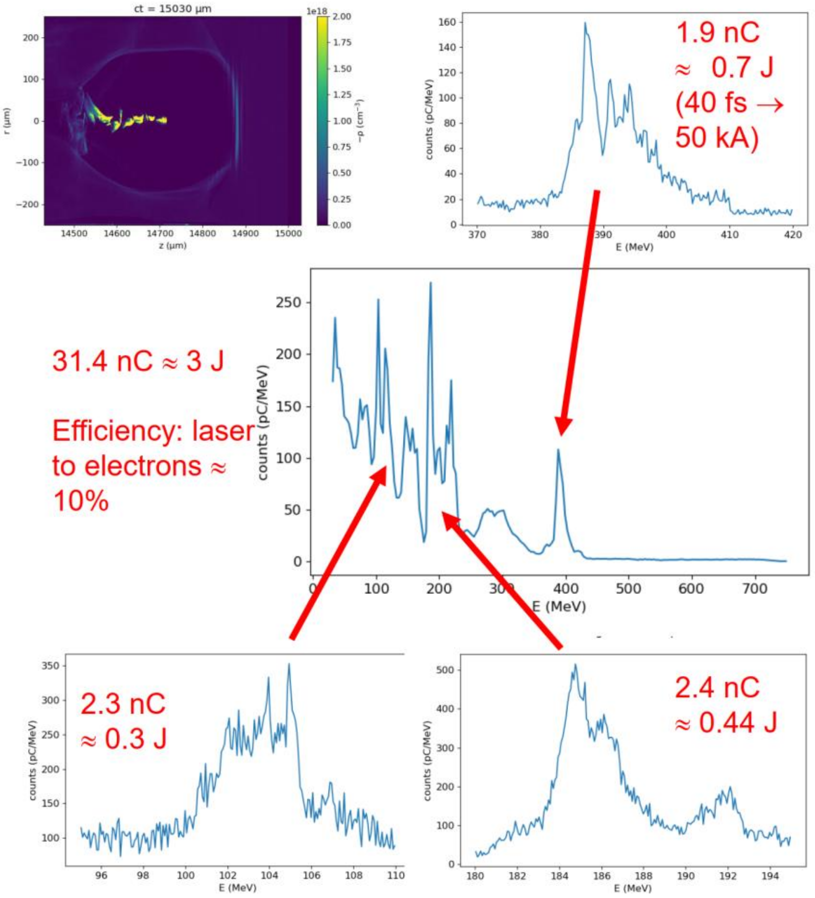

Figure 4: FBPIC simulations using a preformed uniform plasma: λ = 10 μm, $a_0 = 6$ (25 J), n = 5×10^{16} cm^{-3}, $w_0 = 100$ μm, laser pulse duration (FWHM) τ = 300 fs, propagation length 15 mm.

a uniform pre-formed plasma medium with a density of n = 5×10^{16} cm^{-3}. Figure 4 shows that for these parameters the electron spectrum, determined at 15 mm, is quite broad but has relatively narrow bandwidth spectral peaks. Moreover, the total charge produced is more than 30 nC, which shows that the laser energy is converted into electron beam energy with an efficiency approaching 10%, which is very high for a LWFA. Moreover, the electron beam parameters are good: The mean electron beam energy for the highest energy peak is 392.4 MeV and has an r.m.s. spread of 9.5 MeV giving a relative energy spread $\delta\gamma/\gamma \approx$ 2.4%. The normalised emittance is $\varepsilon_n \approx 6.3$ π mm mrad. The electron bunch has the following dimensions at source: σ_x = 5.6 μm, σ_y = 3.4 μm, σ_z = 11.6 μm (bunch duration of 40 fs). The beam divergence in the *x* and *y* planes is half angle $\sigma_{\theta x}$ = 4.5 mrad, $\sigma_{\theta y}$ = 2.3 mrad, respectively.

As an application we consider a CO_2 LWFA producing 130 MeV electrons (Figure 3.) that pass through a 100 period, a_u = 1, 1 cm period undulator, to produce 110 nm radiation. By increasing the energy to 300 MeV (achievable with optimisation) ≈15 nm radiation is produced. The number of photons for a 2 nC (1.25×10^{10} electrons) 400 MeV pulse (in the higher energy spike in Figure 4) is $N_{phot} \approx 2\alpha a_0^2 N_u N_e$ where the fine structure constant $\alpha = 1/137$, and N_u and N_e are the number of periods and electrons, respectively, which gives $N_{phot} \approx 2\times10^{10}$ photons per laser pulse at 82 eV. For 1 kHz this would increase to $\approx 2\times10^{13}$ photons emitted from the undulator per second. By Compton backscattering, a focussed 2 J, 10-cycle CO_2 laser pulse with $a_0 = 1$ backscattering off the 130 MeV beam we obtain $N_{phot} \approx 1\times10^{10}$, 17 keV photons (or 160 keV photons for ≈ 400 MeV electrons). If the CO_2 laser runs at 1 kHz repetition rate then we have a 20 nm source of 10^{14} photons per second, and a 10^{13} photons 33 keV source, which is comparable with synchrotron sources. The LWFA also produces broadband betatron X-rays with a critical energy of 1 keV at a rate of 0.1 photon per electron *i.e.* $\approx 1\times10^9$ per pulse. For a repetition rate of 1 kHz this becomes 10^{12} 33-keV photons s^{-1} directly from the LWFA.

4. CONCLUSIONS

We have shown that an efficient optically pumped ultra-short pulsed CO2 laser can be designed, which would be suitable for many applications including XUV photolithography, remote sensing and driving a laser wakefield accelerator. Quasi-3D PIC simulations show that electron beams with energy up to 100-400 MeV and 10s nC charge can be generated over 8-15 mm acceleration lengths by CO_2 lasers producing pulses with 300 fs duration and 10-25 J energy. In addition, simulations show that ultra-short pulsed 10 μm CO_2 lasers can produce peak longitudinal accelerating fields in plasma of the order 10 TV/m.

ACKNOWLEDGEMENTS

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