BESTIA – the next generation ultra-fast CO₂ laser for advanced accelerator research

Igor V. Pogorelsky, Markus Babzien, Ilan Ben-Zvi, John Skaritka, Mikhail N. Polyanskiy
Accelerator Tests Facility, Brookhaven National Laboratory, Upton, NY USA 11973

ABSTRACT

Over the last two decades, BNL's ATF has pioneered the use of high-peak power CO₂ lasers for research in advanced accelerators and radiation sources. Our recent developments in ion acceleration, Compton scattering, and IFELs have further underscored the benefits from expanding the landscape of strong-field laser interactions deeper into the mid-infrared (MIR) range of wavelengths. This extension validates our ongoing efforts in advancing CO₂ laser technology, which we report here. Our next-generation, multi-terawatt, femtosecond CO₂ laser will open new opportunities for studying ultra-relativistic laser interactions with plasma in the MIR spectral domain, including new regimes in the particle acceleration of ions and electrons.

Keywords: CO₂ laser, pulse compression, strong field phenomena, ion acceleration, laser wake field

1. Introduction

Mainstream experimental research in strong-field physics so far has capitalized on chirped-pulse amplification (CPA) solid-state lasers that have reached petawatt peak power and intensities of 10^{21} W/cm². Interacting with plasmas, these lasers empowered a steep advance towards the next-generation compact sources of energetic electron- and ion-beams that might complement conventional particle accelerators and accelerator-based radiation sources.

Concurrently, there is interest in exploring the capabilities of CO₂ gas lasers as a power source for advanced accelerators. While their peak power hardly competes with that of solid-state lasers, relativistic intensities already are available, while longer wavelengths (~ 10 μ m as opposed to 0.8-1 μ m for solid-state lasers) may offer interesting possibilities due to the different response of matter that mainly is manifested through favorable scaling of ponderomotive energy and critical density.

Answering the quest for more powerful MIR laser sources, the Brookhaven Accelerator Test Facility (ATF) initiated the development of the next-generation high-peak-power (100 TW), ultra-fast (100 fs) CO₂ laser BESTIA (abbreviated from Brookhaven Experimental Supra-Terawatt Infrared at ATF). Operating as the DOE Office of Science user facility, the ATF offers free access to qualified researchers to its lasers and electron beams. A new laser coming on line in 2018 will become an important addition to the research tools available to ATF users.

The paper describes our conceptual approach and recent progress in developing this laser that bestows an unprecedented assortment of new principles never yet applied to high-power CO₂ lasers. The scope includes an all-solid-state optical parametric generator for a seed 10- μ m pulse, isotopic gas-discharge CO₂ amplifiers where natural ¹⁶O atoms are partly substituted with ¹⁸O, a CPA technique, and a patented nonlinear femtosecond pulse post-compression. The laser, focused to its diffraction limit, will be capable of operating to 10^{18} Wcm⁻²; this is the ultra-relativistic intensity for 10 μ m characterized by a dimensionless parameter $a_0 = eE/m\omega c = 10$, where E is the laser's electric field, e and m are, correspondingly, the electron charge and mass, c is the speed of light, and $\omega = 2\pi c/\lambda$ is the laser's frequency. We anticipate a significant impact from achieving the ultra-relativistic conditions in the long-wavelength spectral domain in different areas of the advanced accelerator research.

2. Conceptual approach

High-pressure carbon dioxide (CO₂) lasers currently are the prime tools for generating terawatt-peak-power 10-micron radiation. Presently, Neptune Laboratory at UCLA [1] and the ATF at BNL [2] are the two best-known research facilities in the world that support strong-field physics experiments with CO₂ lasers.

Our motivation for developing a new ultra-fast (sub-picosecond) CO₂ laser technology at the ATF is derived from our historical record of success with the IR laser for several classes of ATF users' experiments. Furthermore, this ultra-

high power (100 TW class) IR laser will offer our users unique opportunities to explore the wavelength scaling of strong-field physics phenomena to $\lambda=10\text{ }\mu\text{m}$ up and the laser-strength parameter $a_0 = 10$.

Achieving nearly a hundredfold gain in peak power, compared with the ATF's present laser, will require our implementing new methods never before applied to IR gas lasers. The present state-of-the-art multi-atmospheric gas-discharge CO₂ amplifiers will be optimized by adding isotopes to assure a smooth gain spectrum envelope, suitable for the seamless amplification of broad-band ultra-short pulses [3]. Compared to solid-state lasers, nonlinear effects in the active medium of gaseous amplifiers are weak, so supporting the attainment of terawatt peak power by directly amplifying picosecond pulses. However, nonlinear pulse distortions in transmissive optics will become critical for the next-generation ultra-intense CO₂ lasers that will operate above tens of terawatts. We can use the CPA technique for mitigating this issue.

Our upgrade plan incorporates four major innovations: An all-solid-state, femtosecond, optical parametric amplifier (OPA) front end [4]; CPA [5]; multiple CO₂ isotopes [3] in the expanded chain of laser amplifiers; and, a nonlinear pulse-compression down to three cycles. Fig. 1 shows a principle diagram summarizing this conceptual approach.

Fig. 1. Block-diagram of the 100-TW mid-infrared laser system BESTIA.

The microjoule sub-picosecond 10-micron seed pulse is generated in an all-solid-state optical parametric amplifier (OPA). The pulse then is chirped and frequency-filtered in a grating stretcher to match the gain spectrum of the CO₂ amplifiers. Stretched to 100 ps, a laser pulse is amplified to ~70 J energy in two high-pressure CO₂ amplifiers isotopically enriched with Oxygen-18. The laser will operate at the 9R rotational-vibrational branch centered at 9.2 μm, which is the strongest one under these conditions with a bandwidth sufficient for amplifying a 1.7-2 ps pulse.

The amplified 100-ps laser pulse then will be compressed in a grating compressor to 2 ps, limited by the spectral width of the 9R branch. At this stage, we will achieve 25 TW peak power. This pulse will be further compressed to the duration of few optical cycles, so exploiting the effect of spectrum broadening via self-phase modulation in nonlinear medium. A patent-pending scheme of a nonlinear pulse compressor [6] will provide an output beam at the 100-TW level and down to 100 fs (three laser cycles) pulse duration.

3. Simulation capabilities

Ability to accurately predict the characteristics of the laser system in different configurations and modes of operation is crucial for the successful design and implementation of the next-generation CO₂ laser. Over the past several years we have developed a sophisticated computer code 'co2amp' suitable for accurate quantitative modelling of ultrashort pulse dynamics in CO₂ amplifiers. The core of the program is a classical model describing the laser pulse amplification in an active medium with discrete spectrum [7]. We supplemented it with the most recent spectroscopic data, added a realistic

model of discharge pumping, Huygens-Fresnel propagation algorithm and sub-routines for various optical elements. Around these, we have built an easy-to-use user interface. Below is a brief list of `co2amp`'s capabilities:

- Large number of active transitions: rotational numbers up to $J=60$, hot- and sequence- bands, isotopic CO_2 .
- Molecular dynamics including realistic pumping, collisional relaxation processes and stimulated transitions.
- Diffraction-based beam propagation through an arbitrary optical system; beam manipulation with common optical elements.
- Linear dispersion and non-linear effects in optical materials (Kerr lensing, self-phase modulation).
- Advanced options: Chirped-pulse amplification, trains of pulses.

The `co2amp` code, routinely used at Brookhaven ATF for a number of years with its proven accuracy and reliability, has been recently detailed in Ref. [8]. The code is used now for design optimization and verification at all stages of the development of our 100-TW CO_2 laser system.

4. Current status of the project

The 100-TW laser full-scale implementation requires massive installation of the new large-volume amplifier, in-vacuum grating compressor, and high-power nonlinear compressor as a part of the major ATF-II upgrade program that involves moving the entire facility to a new, larger location. However, initial development and proof-of-principle tests of the components of the 100-TW CO_2 laser are being performed on the 2-TW CO_2 laser system currently operational at ATF [2].

Below we list the main components of the 100-TW $10\text{-}\mu\text{m}$ laser system with the current status of the design and implementation of each of them.

4.1. OPA-based seed-pulse generator.

An all-solid-state $10\text{-}\mu\text{m}$ seed pulse generator is used as a front end of the present ATF's 2-TW picosecond CO_2 laser and the future ATF-II ultra-fast mid-IR laser system. This seed source utilizes a standard Ti:sapphire MOPA configuration, with a fiber-based oscillator (OneFive Origami-08) and diode-pumped amplifier (Quantronix Integra-HE-07). The oscillator is phase locked to the facility RF clock, which provides the synchronization of laser pulses to the electron beam of the linear accelerator, both used in combination in ATF user's experiments. The oscillator seed is stretched to approximately 150ps and amplified first in a regenerative cavity, and then in a two-pass final amplifier. The spectrum red-shifts to 784nm and pulse duration remains very close to 180fs after recompression. These 7-mJ amplified pulses are then used to pump a femtosecond parametric down-converter (Quantronix Palitra-FS) that utilizes multiple stages for conversion into the mid-IR.

A schematic configuration of this parametric down-converter is shown in Fig. 2. The Ti:sapphire amplifier output is split into three beams; The first is focused into a sapphire crystal and generates white-light continuum that provides the broadband seed for parametric amplification of the tunable signal and idler frequencies. The two remaining beams are the pump for the amplification stages. After the second amplification stage, the signal and idler near 1.4 and $1.7\text{ }\mu\text{m}$, respectively, are mixed and generate a difference frequency near $10\text{ }\mu\text{m}$.

Fig. 2: Principle diagram of a parametric down-converter

The overall bandwidth at the OPA output is much larger than the actual gain spectrum that can be amplified in the CO_2 gain medium. It is filtered in order to match a gain spectrum of a CO_2 laser amplifier. The measured spectra of the seed pulse before and after filtering are shown in Fig. 3 (top). For comparison, we show the gain spectrum of the isotopic regenerative amplifier Fig. 3 (bottom). Spectrum filtering in the stretcher assures our operating the amplifier on a single branch (9R) of the gain spectrum of the CO_2 active medium.

Fig. 3. Top: Pulse spectrum before (a), and after (b) a stretcher. Bottom: Simulated gain spectrum (10 bar, CO₂:N₂:He = 0.35:0.4:9.25; ¹⁶O:¹⁸O = 50:50). The vertical scale is linear.

Table 1 summarizes the main output characteristics of the OPA system.

TABLE 1. Output parameters of the OPA

Wavelength range	8-11 μm
Pulse duration	350 fs
Pulse energy	40 μJ
Repetition rate	240 Hz

4.2. Isotopic amplifiers

Laser amplifiers designed for a million-fold boost the seed pulse energy should match the seed with their spectral gain curve position and a bandwidth. This is ensured by using high-pressure, isotopically-enriched CO₂ gas mixtures excited by powerful high-voltage discharges. Carbon dioxide isotopically-enriched with 50% of oxygen-18 is used in order to provide a superposition of several characteristic gain spectra, each of them being modulated by periodical lines from molecular rotational transitions. Difference in the isotopic mass for a variety of CO₂ molecules (C¹⁶O₂, C¹⁸O₂ and C¹⁶O¹⁸O) results in slight relative spectral shifts and effective blending of several rotational spectra into a smooth quasi-continuum. Such gain spectrum allows seamless amplification of a picosecond pulse without its splitting in a train of pulses, situation typical for laser pulses with periodically modulated spectra [4]. We center the seed pulse on the ‘9R’ rotational-vibrational branch with the maximum gain at 9.2 μm (Fig. 4a) which is the strongest one under this conditions and has a bandwidth sufficient for amplification of a 1.7-2 ps pulse.

The seed pulse from the OPA system is amplified in two 10-bar isotopic CO₂ amplifiers. The first amplification stage uses a commercial amplifier (SDI HP-5) currently operating at the ATF; This UV-pre-ionized, transverse electric discharge laser with an active volume of 1×1.5×80 cm³ is used in the regenerative configuration and provides a ~10⁴ net gain in multiple passes. Our second amplifier will be custom-built by prototyping the design of the currently used terawatt amplifier (Optoel PITER-1). Three identical discharge sections, each having a 10×10×100 cm³ active volume, will be assembled within a six-meter-long high-pressure vessel providing a 3-fold increase in the length of the active medium compared to PITER-1. The 0.2 Hz repetition rate of the Marx generators used to energize the BESTIA amplifier will define the overall repetition rate of the 100 TW laser system. This second amplifier will assure a ~10³ net amplification.

4.3. Chirped Pulse Amplification

The method of chirped-pulse amplification (CPA) is the integral part of present-day ultra-intense laser systems, which normally employ near-infrared ($\sim 1\mu\text{m}$) solid state lasers. We anticipate that employing CPA technique will allow a new breakthrough towards multi-terawatt, ultra-fast mid-IR lasers as well. The use of the CPA scheme is essential for eliminating the limitation on the pulse intensity due to its non-linear interaction with the optical elements and the atmosphere. A damage threshold of optical elements is also expected to be higher for chirped pulses compared to that for picosecond ones.

We are undertaking detailed modeling and optimization of the amplifier configuration using our in-house developed code 'co2amp'. Figs. 4b, 4c, and 4d respectively show the simulated spectrum of the amplified pulse, and the pulse structure before- and after- compression. We see that despite the fairly smooth gain spectral envelope due to the combined broadening of pressure and the effects of isotope mixing (Fig.4a), the exponential enhancement of the pulse's spectrum over the long amplification distance results in its narrowing around the maximum of the 9R branch, along with considerable high-frequency modulation (Fig.4b). This effect, in turn, causes modulation on the temporal envelope of the amplified pulse (Fig.4c). However, CPA compression is hardly affected; Fig.4d shows the pulse recompression to 2 ps FWHM, and an insignificant (2%) after-pulse. This prediction has been further confirmed in proof-of-principle experiments recently completed at the ATF [9].

Fig. 4. Simulations of chirped-pulse amplification: a) Gain spectrum of isotopic 10-bar CO₂ amplifier in the 9-micron region; b) Spectrum of the amplified pulse; c) Temporal profile of the amplified pulse before compression; and, d) Temporal profile of the amplified pulse after compression.

In the reported experiments, the seed pulse has been red-chirped before injecting into the regenerative amplifier. This has been accomplished using a stretcher based on 75 lines/mm replicated ruled gratings. The stretcher allows our expanding a 1-ps pulse to 80 ps. The second function of the stretcher is to act as a band-pass filter to select a part of the spectrum of the seed pulse that matches the desired branch of the gain spectrum.

The amplified pulse is extracted from the amplifier cavity after ten round-trips using the fast semiconductor switch. The maximum energy of the stretched pulse was 29 mJ, measured at the output of the amplifier.

The pulse then is recompressed in a grating compressor. Figure 5 shows the pulse's autocorrelation signal after compression. The duration of the recompressed pulse is 1.6 ps, in good agreement with the pulse's measured spectral bandwidth.

Our stretching of a 1-ps 9- μm pulse to 80 ps improved, by an order of magnitude, the energy extraction from a CO_2 laser amplifier. This is explained by the relieved nonlinear absorption and refraction on the amplifier's optical elements. We consider this accomplishment as a pivotal step towards next-generation ultra-intense CO_2 CPA laser systems for strong-field mid-IR research and applications.

Fig. 5. Autocorrelation plot of the re-compressed amplified pulse. The width of the measured curve corresponds to a 1.6-ps (FWHM) Gaussian pulse.

Implementing the CPA technique through the final stage of amplification in BESTIA should allow a relatively comfortable extraction of the $\sim 70\text{-J}$ laser energy from the final amplifier that, upon recompression with diffraction gratings to ~ 2 ps, should provide ~ 25 TW peak laser power. For further power increase, we plan using a nonlinear femtosecond compressor addressed in the next Section.

4.4 Nonlinear compression

When an intense optical pulse propagates through a medium, the refractive index n of the latter evolves following the intensity profile of the pulse I : $n(t) = n_0 + n_2 I(t)$, where n_0 is the linear component of the refractive index and n_2 is the nonlinear index. A corresponding variation of the phase velocity results in the broadening and chirping of the spectrum of the pulse. This effect is known as self-phase modulation, or self-chirping. Then, a dispersive compressor can be arranged to shrink the self-chirped pulse well below its original duration.

Several issues complicate designing a robust nonlinear pulse-compressor for high-energy pulses:

- Self-lensing due to variation of the effective refractive index across the beam;
- Limited compressibility of the self-chirped pulse caused by different chirping in high-intensity beam center and low-intensity wings of the beam;
- Contribution from low-intensity leading and trailing parts of the pulse limiting overall pulse compressibility;
- Bad reproducibility of the nonlinear effect due to high sensitivity to pulse-to-pulse intensity variation.

We have recently suggested an approach that allows mitigating these difficulties [6]. Our approach is based on the fact that in the case of a Gaussian beam self-phase modulation is always accompanied by self-lensing. We use this effect, normally considered as unwelcome distortion of the beam's collimation, to our advantage by using it for separating high-intensity parts of the pulse/beam where non-linear spectral chirp is strong and nearly linear from low-intensity parts using a simple spatial filter as illustrated in Fig. 6:

We send a laser pulse through a non-linear dispersive medium (e.g. germanium wafer). The effect of the non-linear index on the low-intensity wings of the pulse/beam is negligible. Conversely, the high-intensity peak of the pulse in the central part of the beam undergoes a non-linear transformation that includes both self-phase modulation and self-lensing. Spatial filter, placed in the position of the beam's waist formed by self-lensing, blocks the non-chirped component of the pulse/beam while transmitting the chirped portion. The transmitted beam is then collimated and compressed in a conventional compressor. Either a grating compressor or a negative-dispersion window (e.g. NaCl) can be used as the final compressor. Fig. 7 illustrates simulated results for a 10-micron pulse compression to just two field oscillation cycles.

Fig 6. Non-linear pulse compressor scheme.

Fig. 7. Simulation of a the nonlinear femtosecond pulse compression: Transmitted through a Ge wafer, the pulse experiences frequency modulation with a close to linear frequency chirp observed around its peak (a); experiencing strong self-focusing, this central portion of the pulse will be filtered through a pinhole and recompressed (b).

5. Conclusions

A picosecond CO₂ laser at the Accelerator Test Facility of Brookhaven National Laboratory (Brookhaven ATF) combined with ATF's 80-MeV linear accelerator is a unique instrument supporting researchers coming to the ATF from around the world in exploring particle acceleration in a strong laser field.

A recently initiated program of upgrading the ATF CO₂ laser to the 100-TW level shall be completed within 3 years.

A recently commissioned solid-state OPA was the first step in this upgrade.

A series of high-pressure discharge-pumped amplifiers with isotopic carbon dioxide will boost the energy of the pulse to tens of joules while only minimally distorting its temporal structure. This advantage has been demonstrated already at ATF at a smaller scale with the first operational isotopic regenerative CO₂ laser amplifier.

The CPA technique will be implemented for the first time in a CO₂ laser in order to eliminate effects of Kerr-lensing and self-phase modulation in the active medium and optical components. The first seminal demonstration of CPA in molecular gas lasers has been reported recently from ATF.

Finally, we plan to further increase pulse peak-power to ~100TW (10J in 100fs) via nonlinear pulse compression; this is arguably the most innovative part of the upgrade plan that requires considerable research and development.

Our current plan is to complete the 25-TW 2-ps CPA CO₂ laser in 2017 and equip it with a nonlinear 100-fs compressor in 2018. BESTIA will be offered to users as a part of the ATF-II facility. The availability of a 100-terawatt-class 10-micron laser will open up invaluable opportunities for innovative research in strong-field physics and advanced accelerator design within a range of parameters not accessible previously with mid-IR lasers. For these studies, the ATF-II provide its users with two radiation shielded experimental areas for strong-field physics research (see Fig.8). In one experimental hall, the BESTIA laser beam will be brought to interaction with femtosecond, multi-MeV electron bunches in vacuum or plasma enabling advances studies in laser wakefields, inverse Compton scattering, inverse FEL acceleration, etc. The second experimental hall will be dedicated to laser interaction with gas- and material- targets for Ion Acceleration, THz radiation and other user-inspired experiments.

Fig. 8. A fragment of a floor plan of the ATF-II facility shows the 100-TW CO₂ laser BESTIA and laser experimental areas

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References

- [1] <http://pbpl.physics.ucla.edu/Research/Facilities/Neptune/#Laser>.
- [2] <http://www.bnl.gov/atf/capabilities/CO2laser.php>.
- [3] M. N. Polyanskiy, I. V. Pogorelsky, V. Yakimenko, Optics Express 19 (2011) 7717.
- [4] M. N. Polyanskiy, M. Babzien, "Ultrashort Pulses," in CO₂ Laser - Optimisation and Application, InTech (2012) 139-162.
- [5] D. Strickland, G. Mourou, Opt Commun. 56 (1985) 219.
- [6] M. N. Polyanskiy, U. S. Patent application No. 62/021725 (8 July 2014).
- [7] H. C. Volkin, J. Appl. Phys. 50 (1978) 1179.
- [8] M. N. Polyanskiy, Appl Optics 54 (2015) 5136
- [9] M. N. Polyanskiy, M. Babzien, I. V. Pogorelsky, Optica 2 (2015) 675