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BESTIA – The next generation ultra-fast CO_2 laser for advanced accelerator research

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ABSTRACT

Over the last two decades, BNL's ATF has pioneered the use of high-peak power CO_2 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 CO_2 laser technology, which we report here. Our next-generation, multi-terawatt, femtosecond CO_2 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.

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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/cm^2. 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 CO_2 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 ($\sim$10 μm as opposed to 0.8–1 μm 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) CO_2 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 CO_2 lasers. The scope includes an all-solid-state optical parametric generator for a seed 10-μm pulse, isotopic gas-discharge CO_2 amplifiers where natural ^{16}O atoms are partly substituted with ^{18}O, 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} W cm^{-2}; this is the ultra-relativistic intensity for 10 μm characterized by a dimensionless parameter $a_o = \frac{eE}{m\omega c} = 10$, 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 $\omega = \frac{2\pi c}{\lambda}$ 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 (CO_2) 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 CO_2 lasers.

Our motivation for developing a new ultra-fast (sub-picosecond) CO_2 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 $\lambda = 10$ μm up and the laser-strength parameter $a_o = 10$.

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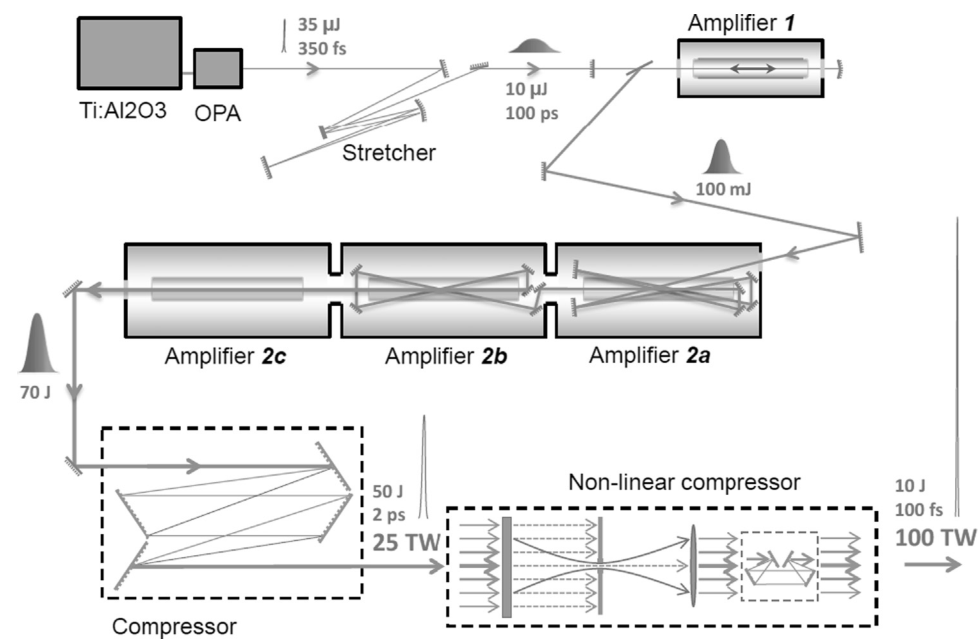

Fig. 1. Block-diagram of the 100-TW mid-infrared laser system BESTIA.

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 CO_2 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 CO_2 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 CO_2 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.

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 CO_2 amplifiers. Stretched to 100 ps, a laser pulse is amplified to ~70 J energy in two high-pressure CO_2 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 CO_2 laser. Over the past several years we have developed a sophisticated computer code ‘co2amp’ suitable for accurate quantitative modeling of ultrashort pulse dynamics in CO_2 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].

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