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MULTI-TERAWATT, SUB-PICOSECOND LONG-WAVE INFRARED LASER FOR NEXT-GENERATION PARTICLE ACCELERATORS*

M. N. Polyanskiy†, I. V. Pogorelsky, M. Babzien, W. H. Li, R. Kupfer[1], M. A. Palmer,
Brookhaven National Laboratory, Upton, NY, USA
N. Vafaei-Najafabadi, Stony Brook University, Stony Brook, NY, USA
[1]now at Lawrence Livermore National Laboratory, Livermore, CA, USA

Abstract

We provide an update on the current status and outline the future development plans for the multi-terawatt long-wave infrared (LWIR) laser system at Brookhaven National Laboratory's Accelerator Test Facility (ATF). This report sheds light on our advancements and strategic road map for this research tool.

INTRODUCTION

Certain regimes of laser-based particle acceleration, including laser-wakefield acceleration of electrons at low plasma densities and the acceleration of ions from gaseous targets, prefer long wavelengths due to the lambda-squared scaling of the ponderomotive potential [1].

At present, achieving multi-terawatt levels of peak power at long-wave infrared (LWIR) wavelengths around 10 µm is possible only through the amplification of a picosecond laser pulse in high-pressure CO_2 laser amplifiers. Our state-of-the-art LWIR laser system can deliver up to 5 TW peak power in 2-picosecond pulses [2].

We are actively developing a next-generation LWIR laser that will offer a sub-picosecond pulse duration and a peak power of up to 25 TW. Theoretical models suggest that these laser parameters will enable us to explore new acceleration regimes, such as the blow-out regime of laser-wakefield acceleration with macroscopic (~300 µm) accelerating plasma structures.

CURRENT STATUS OF THE ATF LWIR LASER

ATF Expertise

The state-of-the-art picosecond LWIR laser currently in operation at the ATF has demonstrated peak power up to 5 TW, with 2 TW routinely delivered to user experiments via an in-air beam transport line. This system, schematically illustrated in Fig. 1, employs a hybrid master oscillator-power amplifier (MOPA) scheme. Here, the seed pulse generated by a solid-state laser is amplified in discharge-pumped gas laser amplifiers. A high-pressure mixture of three CO_2 isotopologues provides a gain spectrum with (sub-)picosecond bandwidth. Fig. 2(a), (b), and (c) present the gain spectrum of the CO_2 amplifiers, as well as the spectrum and temporal structure of the output pulse, respectively. Notably, the ATF's LWIR laser is the first gas laser to implement the chirped-pulse amplification (CPA) scheme.

2023 Upgrade

The current peak power at the interaction point is limited to ~2 TW due to nonlinear interactions, including undesirable self-focusing and self-phase-modulation, with the IR windows (typically made of sodium chloride, NaCl) and the atmosphere. Currently, we are in the process of commissioning a new compressor chamber and an in-vacuum transport system. This upgrade will prevent the compressed pulse from passing through any material, thereby enabling delivery of a full-energy pulse with up to 5 TW peak power to the interaction point. Moreover, this development will pave the way for further peak-power upgrades, which are discussed in the following section.

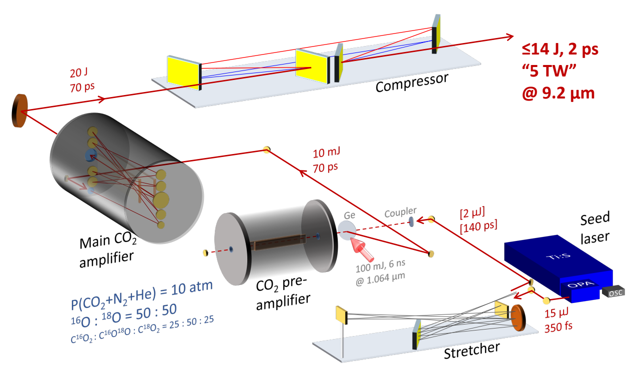

Figure 1: 5 TW.

R&D FOR FUTURE UPGRADES

ATF is actively engaged in research and development efforts to further enhance the peak power of the LWIR laser. The near-term goal is to exceed 10 TW peak power and reduce pulse duration to less than 1 ps, in line with the requirements for achieving an efficient "blow-out" regime of laser wakefield acceleration sought by ATF's user community. We are contemplating two potential upgrades, each capable of attaining the aforementioned pulse parameters. Ultimately, combining both upgrades should enable a reduction in pulse duration to approximately 100 fs (3 optical cycles) and an achievement of 25 TW peak power. In the following discussion, we assume this ultimate configuration.

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† polyanskiy@bnl.gov

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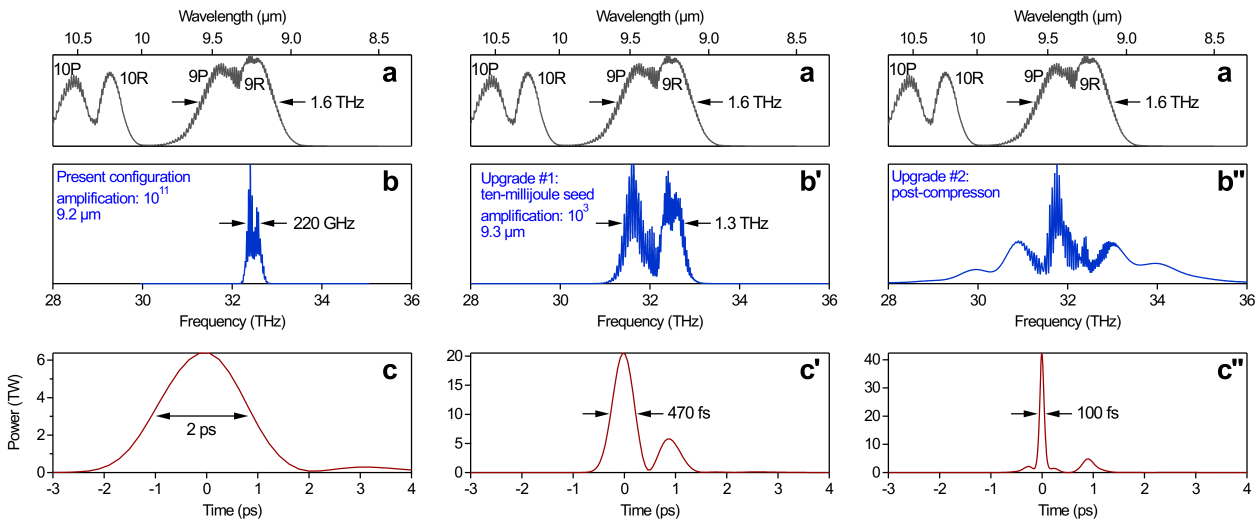

Figure 2: Peak power upgrade road map.

High-Energy Solid-State Seed

The current system constrains pulse duration to approximately 2 ps due to gain narrowing during the 11-orders-of-magnitude amplification process. This significant level of amplification is essential to boost the pulse energy from the microjoule- to tens-of-joules level (a 7 orders of magnitude increase) and to offset the losses in the first CO_2 amplifier, which is arranged in an inherently lossy regenerative configuration (a 4 orders of magnitude loss on 16 round-trips). By elevating the seed energy to around 10 mJ and eliminating the regenerative CO_2 pre-amplifier, we can reduce amplification to just 3 orders of magnitude, thereby reducing the gain narrowing and enabling a 500 fs pulse. Figures 2(b') and (c') show the results of numerical modeling of such a system. Accounting for a contingency factor of approximately 20 % for possible real-life system imperfections, we anticipate reaching at least 15 TW peak power following this upgrade. We are presently evaluating various methods of generating a 10 mJ LWIR seed pulse; at present, a Raman/DFG and OPCPA-based wavelength conversion schemes with a 2 μm Ho:YLF pump appear to be the most promising approaches.

Post-Compression

Post-compression schemes, in which the spectrum of a pulse at the laser's output is broadened via self-phase modulation in a nonlinear material characterized by a nonlinear refractive index n_2, followed by compensating the resulting chirp to reduce pulse duration, offer a pathway to surpass the pulse duration limit imposed by the gain bandwidth of the laser's active medium. We recently proposed and demonstrated a proof-of-principle two-bulk-material scheme for the post-compression of an LWIR pulse. This scheme capitalizes on the negative group velocity dispersion (GVD) exhibited by the majority of materials at LWIR wavelengths and utilizes a combination of two elements with optimal n_2/GVD ratios.

The proof-of-principle demonstration, performed at reduced energy, is schematically shown in Fig. 3 [3]. In this setup, a stable intensity distribution crucial for scheme performance was achieved through a lossy but robust setup that relies on far-field diffraction on a hard-edge aperture. The 2-picosecond pulse was compressed to ~300 fs in the beam's center and to <500 fs integrated across the entire beam. We are currently developing a full-energy setup with efficient spatial filtering, and initial experimental tests are planned for the next few months.

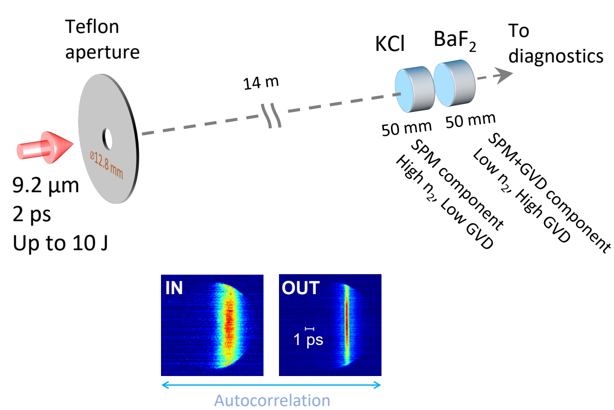

Figure 3: Proof-of-principle experiment for post-compression.

Combining post-compression with the seed energy upgrade can reduce the final pulse duration to 100 fs, as demonstrated by our numerical modeling in Fig. 2(b") and (c"). In this case, we propose a scheme where the two bulk materials of our post-compressor simultaneously serve as the lenses of a spatial filter setup, as shown in Fig. 4. The results displayed only account for the usable part of the beam contained in the first diffraction maximum after focusing to an interaction point (IP). Once again, we apply a 20 % contingency factor to arrive at a realistic estimate of the achievable peak power of ~25 TW.

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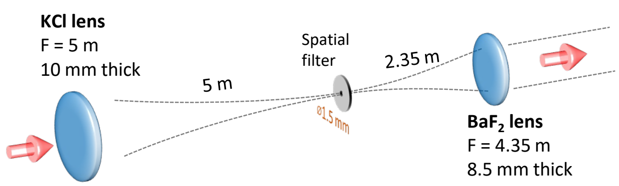

Figure 4: Design of future post-compressor for 500 fs to 100 fs compression.

Optical Pumping

Laser-based particle acceleration schemes have attained a certain level of maturity. Although they are not yet primed for practical application, the question of whether the underlying technologies can meet the demanding requirements of, for instance, industrial or medical applications, now warrants careful consideration. While ATF's LWIR laser is a unique research instrument, its low repetition rate (one pulse per minute) is currently the most significant issue that needs addressing as we prepare for the transition of laser accelerators from research facilities to broader applications.

Our long-term vision for enhancing the performance of LWIR laser systems with CO_2 amplifiers involves transitioning from electric-discharge to optical pumping—a pumping scheme that has proven its robustness over decades of use in solid-state lasers. Eliminating the need for megavolt-class pulse-forming networks, which are required for the discharge pumping of terawatt amplifiers, paves the way to achieving practically interesting repetition rates on the order of 100 Hz and beyond. Moreover, optical pumping can improve pulse-to-pulse stability, simplify the optimization of gas composition, and dramatically reduce the size of the amplifier [4].

Our estimates indicate that pumping a laser amplifier similar to the final amplifier of ATF's laser would require approximately 1 kJ of pumping energy in less than 1 µs optical pulses at 4.3 µm (ideally) or 2.8 µm (with reduced efficiency). Currently, Fe:ZnSe and Er:YSGG lasers are being considered for optical pumping at these two wavelengths, respectively. In the long term, GaSb laser diodes could present an optimal solution for a diode-pumped gas (DPG) laser. Figure 5 presents a conceptual schematic of an optically-pumped CO_2 amplifier, with parameters approximating those of a laser similar to the one at ATF.

CONCLUSION

This paper has outlined the current status and future development plans for the multi-terawatt long-wave infrared (LWIR) laser at the Accelerator Test Facility (ATF) of Brookhaven National Laboratory. The existing system, operating at peak power levels of up to 5 TW, is undergoing further development to enhance its performance by increasing the peak power to up to 25 TW and reducing the pulse duration to a hundred-femtosecond level. Advanced strategies, such as increasing the energy of the seed pulse and implementing post-compression techniques, are being explored to achieve these goals. Furthermore, the long-term vision includes a transition from electric-discharge to optical pumping, aiming to improve the repetition rate, stability, and compactness of the system. With these innovations, we strive to meet the demanding requirements of various applications, including industrial and medical applications, propelling the field of laser-based particle acceleration to new heights.

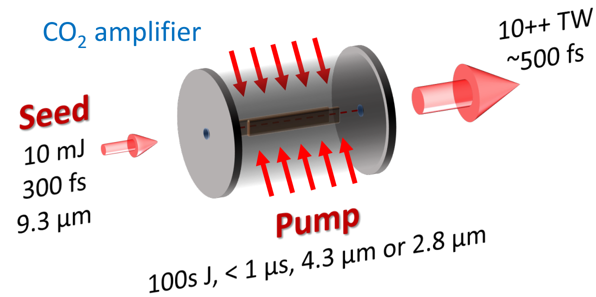

Figure 5: Conceptual schematic of a high-energy, high-pressure CO_2 laser amplifier with optical pumping.

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