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CO_2 CPA LASER DEVELOPMENT FOR USER EXPERIMENTS IN ADVANCED ACCELERATORS AND RADIATION SOURCES*

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Abstract

Development of a next-generation ultrahigh peak power mid-IR (~10 µm) laser is underway at the Accelerator Test Facility. Recent implementation of a chirped-pulse amplification scheme opens the way to an order-of-magnitude increase in the achievable peak power.

INTRODUCTION

The Accelerator Test Facility (ATF) at Brookhaven National Laboratory is a U.S. Department of Energy Office of Science National User Facility for advanced research in accelerator physics and technology. The ATF's terawatt-class CO_2 laser is a unique scientific instrument allowing researchers to explore new particle acceleration mechanisms and to study light-matter interactions at a longer photon wavelength, $\lambda_{CO2} \sim 10$ µm, than is available at most other research facilities

Developments over the last 25 years have brought the peak power of ATF's laser system to the limit achievable in a conventional gas laser MOPA configuration (~0.5 TW in routine operation, and up to 1 TW in some experiments) - limited by non-linear pulse interaction with salt optics. To overcome this limit, we have implemented, for the first time in a gas laser, a chirped pulse amplification (CPA) scheme with the goal of demonstrating 3-5 TW peak power at the system output. We aim to deliver a large fraction of this power as a high-quality beam to a range of user experiments at the current ATF. Achieving this goal will validate our design concept for implementing a higher power system as part of the ATF-II upgrade. Our present design targets initial operation of that facility will deliver >10TW, 2ps pulses to users. This initial configuration will support development of pulse compression techniques to provide sub-ps pulses with 10s-100 TW peak power for the study of advanced acceleration techniques.

STATE OF THE ART

The ATF CO_2 laser employs a master oscillator - power amplifier (MOPA) configuration (Fig. 1). A commercial solid-state Optical Parametric Amplifier (OPA) system (Onefive Origami / Quantronix Integra / Quantronix Palitra) provides a microjoule, 350 fs (FWHM) seed pulse. This pulse is chirped in a grating stretcher and amplified in a series of high-pressure CO_2 amplifiers. A regenerative amplifier (SDI HP-5) amplifies the pulse to the 10-mJ level and a large-aperture, multipass final amplifier (Optoel Piter-I) provides output pulses that can reach 20+ J. The final

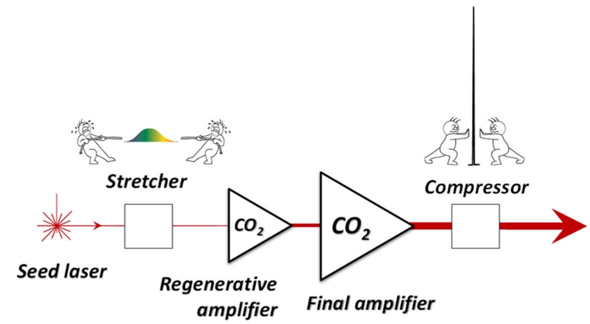

Figure 1: Block-diagram of ATF's TW mid-IR laser.

amplifier output pulse is compressed in a grating compressor. The minimum pulse width is limited to several picoseconds by the gain bandwidth of the CO_2 active medium.

Implementing an Isotopic CO_2 Active Medium

The gain spectrum of an atmospheric-pressure CO_2 laser amplifier consists of a comb of narrow rovibrational lines (Fig. 2). Such an amplifier is unsuitable for amplifying a picosecond pulse that has a broad spectrum overlapping several lines in the gain spectrum (Fig. 2, Insert). The gain spectrum can be smoothed by operating at elevated pressures where individual spectral lines broaden and partially overlap (Fig. 2, "*10 bar*"). Residual spectral modulation, however, results in the amplified pulse being split into a series of sub-pulses spaced by the inverse of the frequency of spectral modulation (~20 ps).

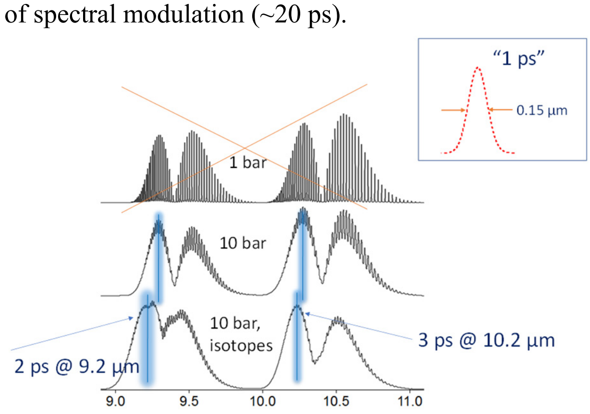

Figure 2: Gain spectra for CO_2 laser amplification at atmospheric pressure and at 10 bar, and for isotopically-enriched CO_2 at 10 bar. Insert: the transform-limited spectrum of a 10-µm 1-ps (FWHM) pulse.

Nearly complete elimination of the spectral modulation can be achieved when isotopically-enriched CO_2 is used.

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The overlapping spectra of properly selected isotopologues results in a smooth gain spectrum suitable for amplification of 2-3 ps pulses (Fig. 2, "*10 bar, isotopes*"). This approach, using a mixture with 50% ^{18}O, was pioneered and is in normal use by the ATF in its regenerative amplifier system [1]. Preparations are now in place to begin operating the final amplifier system with a similar isotopic mixture starting in July 2018. This will reduce the width of the currently available ~4 ps laser pulses to ~2 ps and will also eliminate the ~30% loss of laser energy from the main pulse due to pulse splitting.

Chirped Pulse Amplification

In contrast to ultrashort-pulse solid state laser systems, CPA was not considered until recently in gas laser systems due to the small nonlinear index of refraction in gases compared to that in laser crystals. During the development and optimization of the ATF CO_2 laser amplifiers, it was found that non-linear interactions (self-focusing and self-phase modulation) in the amplifier windows and intra-cavity transmissive optics limit the achievable peak power. The introduction of CPA techniques is thus critical for achieving peak powers at the terawatt level.

To the best of our knowledge, gas laser amplification with CPA was first implemented with the ATF's regenerative amplifier [2]. This resulted in an immediate increase of extracted energy by an order of magnitude and a factor of 5 improvement in overall system performance when taking into account a 50% net transmission through the compressor optics. Our research indicates that further improvements in energy extraction are possible with larger chirp.

Recent upgrades have extended the CPA configuration to include both the ATF regenerative and final amplifiers. An in-air compressor, consisting of four replicated ruled gratings (Richardson Gratings) with154×206 mm^2 active area and 75 grooves/mm, can handle 12-15 J of energy in a Gaussian input beam and provide ~50% transmission.

Isolating Reflections from User Experiments

Many experiments at the ATF, such as ion acceleration and laser wakefield acceleration studies, send a tightly-focused laser beam into a dense plasma. A substantial fraction of the laser energy is reflected by the plasma and can propagate back through the laser system resulting in further amplification and potential damage to optical elements in the amplifier chain. In order to deliver the highest power to users, these back-reflections, with their significant potential for system damage, must be mitigated. This issue has been addressed by the implementation of a high-power optical isolator or plasma shutter [3], which decouples the final amplifier from the user experiments. A diagram of the current ATF plasma shutter is shown in Fig. 3.

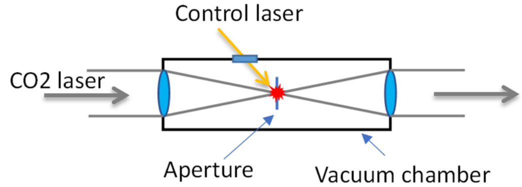

Figure 3: Diagram of the ATF plasma shutter.

Before transmission to an experiment, the output laser beam is focused on a 2-mm diameter graphite pinhole by a NaCl lens that also serves as the input window to a vacuum chamber. A second NaCl lens (output window) re-collimates the beam. After the CO_2 laser pulse has passed through the pinhole, a control laser pulse (nanosecond YAG), which is focused on the edge of the pinhole, is fired. This creates a plasma cloud to block the pinhole opening and prevent any reflected power from propagating back into the amplifiers and causing damage.

FACILITY R&D AND UPGRADES

In early 2017, funding was received for a focused R&D program to conduct detailed tests of the laser system elements required for the ATF-II upgrade. The primary goals were to mitigate any remaining risks for the laser portion of the ATF-II plan and also to leverage those studies to improve laser performance for users at the current ATF. Results from this R&D program are now being applied to upgrades of the present ATF laser system. They are also being incorporated into our designs and operating projections for the new ATF-II laser system, which is presently under construction. The following sections briefly summarize the key findings of the R&D program and associated system upgrades. Projections for future performance of both the ATF and ATF-II laser systems are provided.

Energy Extraction and Beam Quality

Regenerative Amplifier Modifications The optics in the regenerative amplifier were re-configured to improve energy extraction and reliability. Implementation of a reflective intra-cavity telescope reduced loads on the internal semiconductor optical switch, thus doubling system output. New output optics were installed to optimize beam delivery to the final amplifier. An active optical isolator (Pockels cell) at the amplifier input was replaced by a passive isolator (Faraday rotator) to improve reliability.

Main Amplifier Modifications Increased input energy to the final amplifier allowed a reduction in number of passes from 12 to 8 without compromising the output energy. A new record energy output of 23 J, versus 18.5 J previously, was demonstrated. The simplified optics with improved design and optimized configuration and resulted in greatly improved shot-to-shot pointing stability and beam quality. A quasi-Gaussian ($M^2 \leq 2$) beam is reliably produced and delivered to experiments. The electrical discharge circuits in the amplifier were refurbished and optimized, which resulted in significantly improved shot-to-shot reproducibility of the output energy.

Beam Transport Modifications The beam transport system was redesigned to minimize the elements and to increase the aperture of individual components. This allowed substantial elimination of beam distortions and minimized the frequency of optical damage to the optical elements.

Chirped Pulse Amplification

Grating Damage Thresholds Damage threshold measurements for aluminium-coated replica diffraction gratings show a 0.5-0.7 J/cm^2 limit for picosecond, 10-µm pulses. A

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reflective telescope system was designed and installed to utilize the full surface area of the gratings, thus maximizing the total energy achievable at system output. In this configuration, the compressor can safely handle 12-15 J of input energy, thus delivering 6-7 J at the output. Tests were conducted with input shots of up to 20 J (corresponding to 10 J CPA output) without visible damage, thus providing confidence in the safety margin. Procurement of gold-coated gratings will increase the safe operating energy.

Chirp Parameters In the present CPA configuration, the amplified chirped pulse is ~20 ps (FWHM) long. With this relatively small stretching, self-phase modulation (SPM) begins in the main amplifier output window at ~10 J. SPM results in the appearance of non-chirped component in the pulse, thus preventing its efficient re-compression to the transform-limited width. The switch to isotopic CO_2 in the main amplifier will significantly eliminate this issue – use of a fully isotopic amplifier chain will double the bandwidth and double the chirp. Implementing new compressor gratings with higher density grooves (100/mm *vs.* 75/mm at present) will provide a second doubling of the chirped pulse length and minimize any SPM in the output window.

Isotopic Final Amplifier

Isotope Implementation The main amplifier gas system was refurbished to ensure integrity for the switchover to the rather expensive isotopic gas mixtures. An isotope recovery system has been prototyped and the final version is currently being implemented. Isotope delivery is expected within the next few weeks and a transition to isotopic operations is planned for July 2018.

Isotopic Operation Switching to operation with isotopic mixtures in the main amplifier will reduce its gain by a factor of 4 based on our current modelling. This decrease can be mostly (or fully) compensated by the improved energy extraction from the regenerative amplifier with both systems operating at an optimized wavelength of 9.2 μm. In the event that 20 J output from the main amplifier is not achieved in this configuration, we will be able to add additional passes through the active volume to compensate.

Laser Delivery to Users

A plasma shutter, as described above, is currently in use for standard operation. It reliably eliminates reflections to a level harmless for the laser system. An improved design is presently in fabrication. In the new design, the plasma shutter shares a vacuum volume with a transport line to the experimental chamber. NaCl lenses replaced by parabolic mirrors and the compressed pulse passes through a single transmissive element, a large-diameter NaCl entrance window - thus reducing parasitic reflections and nonlinear effects. The transport line provides 100 mm clear aperture at each turning mirror and 140 mm ID in the transport path, thus minimizing energy loss and beam distortions.

Performance Projections and Future Plans

Implementation and optimization of isotopic operation of the final amplifier along with incorporation of all updates to the CPA configuration will enable further increases in the output power of the present ATF CO_2 laser. Utilization of stronger chirp and higher damage threshold compressor gratings will provide a 20 J, 80 ps chirped pulse at the output of the final amplifier. With our projected transmission efficiency through the CPA, we expect overall system output of a single pulse with 10 J and 2 ps width, corresponding to 4.7 TW peak power. Demonstration of this performance will validate the key design assumptions for the ATF-II laser system. Delivery of this power to users at the current ATF will still be limited by the laser transport system (including the plasma shutter). At present, based on the threshold of the nonlinear interaction in the transmissive optics, we project that the ATF system will safely deliver 2 TW to in-vacuum user experiments. Delivery of higher power will be explored but can't be guaranteed. Higher power will be available for other user experiments such as exploring laser channeling in air.

The ATF-II design provides for: a 3× increase in the active volume in the final amplifier; a vacuum CPA system with higher efficiency gratings, which also have higher damage thresholds; and no transmissive optics between the CPA and the experiments. The larger active volume in the main amplifier will allow generation of higher energy pulses while the all-vacuum compressor and transport line design will address the issue of handling that energy and delivering it to an experiment with minimum losses.

Initial operation (corresponding to our proposed Key Performance Parameter for the upgrade project) is based on the extraction of 50 J from the new final amplifier. After the CPA (assuming no improvements to the present transmission efficiency), this would correspond to 10 TW (20J and 2 ps) being delivered to the first users of the new system. Transmitting a high quality gaussian beam, with a 50 J energy, through the presently planned 100-mm diameter NaCl output window is particularly challenging. We are pursuing two approaches to address this issue: 1) use of a super-Gaussian beam on the window that can be achieved by using variable-reflectivity mirrors and/or apodizing filters in the amplifier, and 2) implementing a larger output window that is capable of handling the 10 bar amplifier pressure. After reaching the 10 TW milestone, R&D aiming at system optimization and improvement will continue. In particular, implementation of nonlinear pulse compression (NLPC) techniques, with the goal of providing sub-ps laser pulses with at least tens of terawatts peak power, will be pursued. In the long term, our goal is to achieve 100 TW pulses, which is of particular interest for demonstrating the potential of laser wakefield acceleration schemes at 10 μm.

In conclusion, Table 1 summarizes historical and projected laser parameters for the mid-IR lasers of the ATF.

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Table 1: ATF Laser Parameters

	2016	2018	ATF-II, Day 1	ATF-II, NLPC
λ (um)	10.3	9.2	9.2	9.2
τ_{pulse} (ps)	4	2	2	<1
Energy (J)	3	4.5	20	≥10
Main pulse (%)	70	100	100	100
Peak Power (TW)	0.5	2	10	10-100

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