EPJ Web of Conferences **309**, 07002 (2024)
EOSAM 2024
https://doi.org/10.1051/epjconf/202430907002

80 W, up to 2 mJ Yb-based laser multi-pass-cell post-compression down to sub-20 fs: experimental and numerical results.

Jean-François Hergott*, *Fabrice* Réau, *Nicolas* Lericheux, *Matthieu* Guer, *Hugo* Marroux, *Romain* Géneaux, *Olivier* Tcherbakoff, *Fabien* Lepetit, *David* Bresteau, *Thierry* Ruchon, *Pascal* Salières, *Thierry* Auguste and *Pascal* D'Oliveira

Université Paris-Saclay, CEA, LIDYL, 91191 Gif-sur-Yvette, France

Abstract. In the last years, different methods of laser pulse post-compression have proven their efficiency. Nonlinear spectral broadening achieved when coupling an ultrafast pulse in a gas-filled multi-pass-cell (MPC) provides common pulse compression factors of 10 to 20, depending on the initial pulse duration. We report here on the compression of up to 2 mJ, 330 fs pulses of an Ytterbium (Yb) based laser down to sub-20 fs (compression factor of 17), using argon-filled MPCs, at the limit of temporal pulse breakup. Numerical calculations reproducing the experiment data, and demonstrating the importance of the driver pulse profile on the shape of the broadened spectra, are discussed.

During the last years, Yb-based laser sources at high repetition rate (several tens of kHz) with pulse energy in the mJ-range are commercially available. Despite their robustness, ease of use, they exhibit a pulse duration of several hundreds of femtoseconds (fs), which is not appropriate for high intensity applications. It is possible to overcome this limitation by using spectral broadening techniques coupled to post-compression, and reaching the sub-40 fs range. Different techniques exist [1] but the commonly used are based on coupling the pulse either in a gas-filled stretched hollow-core-fiber (HCF) [2, 3], largely developed on Ti:Sa-based lasers to reach few cycle regime and in gas-filled or bulk multi-pass-cells (MPC) [4, 5]. This last technique, now mature, ensures higher transmission, above 90%, than HCF. MPC post-compression at high average power of Yb-based lasers offers now a real alternative to Ti:Sa lasers when high repetition rates, above 10 kHz, are necessary

In this paper, we demonstrate MPC post-compression of 80W Yb-based lasers down to sub-20 fs. We use a commercial Yb-doped laser system (Carbide, Light Conversion) with a pulse duration of 330 fs FWHM centered 1030 nm. The output pulse energy can be easily tuned up to 2 mJ while keeping an average power of 80 W. Two main modes leading to two different MPC set-ups have been studied. Set-up 1 for pulse energies between 400 µJ and 800 µJ at respectively 200 kHz and 100 kHz repetition rates, and set-up 2 for 2 mJ pulses at 40 kHz repetition rate, as shown in Fig 1. We will call them respectively LE and HE mode for low and high energy in the rest of the paper. The measured output beam $M^2_{x,y}$ varies slightly from 1.1 × 1.12 to 1.12 x 1.09, and the beam diameter from 5 mm to 5.2 mm at 1/e^2, with 98 % circularity, in LE and HE modes respectively, as shown in the inset in Fig 1. Two different MPC set-ups are necessary for achieving the right intensity at the cavity focus in order to favor self-phase-modulation (SPM) over ionization and self-steepening.

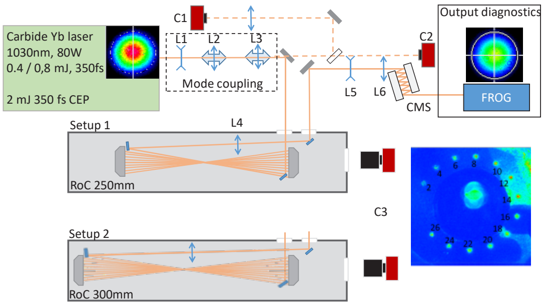

Fig. 1. Schematic of the post-compression setup composed of a mode-matching optical system with three lenses L1, L2 and L3, an argon-filled single-stage MPC, a convex lens L4 for collimation followed by a magnification telescope (L5 and L6) and a set of two chirped mirrors (CMS) for post-compression. C1 and C2 are cameras imaging the near field and far field of the beam to ensure alignment in the MPC. Camera C3 images the transmitted pattern by a cavity mirror. Two different MPC based on two low-GDD cell mirrors set-ups are used depending on the input energy; setup 1 up to 800 µJ and setup 2 for 2 mJ pulses

The overall experimental setup (Fig. 1) consists of a mode-matching lens telescope coupled to a focusing lens, a MPC placed in an argon-filled chamber allowing up to 4.5 bars pressure, a collimation telescope and a chirped-mirror compressor. Depending on the energy of the pulse, the MPC is based on two 2" concave dielectric low GDD mirrors (around 0 fs^2) with a radius of curvature (ROC) R= 250 mm or R= 300 mm. The distance between the mirrors is L= 495 mm for the LE mode and 595 mm in the HE mode i.e., an L/R ratio of 1.98 in both cases. These configurations allow for increasing the intensity at focal plane in set-up 1 mode and lowering the energy density on the mirrors in in set-up 2. A cavity mode-matching

---

[*] Corresponding author: jean-francois.hergott@cea.fr

optical system, composed of three lenses L1, L2 and L3 with respective focal lengths of −100 mm, 200 mm and 1500 mm is used for focusing the laser beam. Small rectangular dielectric mirrors (10 mm × 25.4 mm) are positionned at both ends of the cell. Injection is performed at 45° and extraction close to 0° at pass 27 for both modes. As it appears on the pattern image used to optimize the pulse coupling (Fig 1), the waist size changes slightly at each reflection. A first 300 mm focal length lens collimates the beam, and a magnification telescope enlarges the beam diameter to 10 mm (at 1/e2) to enter the chirped-mirror compressor with 80 W average power (400 µJ,200 kHz – 800 µJ, 100 kHz - 2 mJ, 40 kHz).

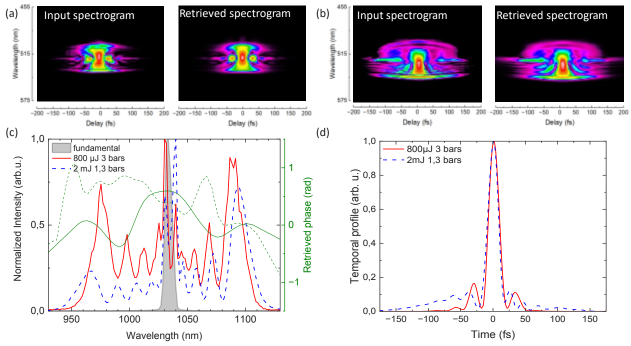

Fig. 2. Input and retrieved single shot SHG-FROG spectrograms for (a) 800 µJ and (b) 2 mJ pulses coupled at 80 W in MPC set-ups filled with 3 and 1.3 bars of argon, respectively. (c) Corresponding measured spectra (solid red and dashed blue lines). In grey, input spectrum. In solid and dashed green lines, retrieved spectral phases. (d) Corresponding retrieved temporal profiles leading to respectively 18.4 fs and 19.5fs FWHM pulse duration in LE and HE modes.

Each chirped mirror allows up to seven reflections with - 200 fs^2 per bounce dispersion compensation. The number of passes in the compressor is optimized for each set-up, and pressure. Respectively 12 and 6 reflections are needed for post-compressing the 800 µJ pulse at 3 bars (set-up 1) and the 2 mJ pulse at 1.3 bars (set-up 2). In Figs 2 a) and b), we show the respective input and retrieved spectrograms obtained with a single shot SHG-FROG (Femtoeasy) with an average error below 2.10^{-2}. In Fig. 2 c), one can observe the spectral broadening obtained in each case (red and blue lines) compared to the initial spectral width. The broadening is almost similar for the two energies with a higher spectral asymmetry in the 2 mJ case. It is likely due to the higher intensity achieved at the focus in this case, which leads to an increase of the self-steepening, compared to the low energy case. The FROG retrieved temporal profiles shown in Fig. 2 d) give 18.4 fs and 19.5 fs FWHM pulse durations for respectively 800µJ and 2mJ, while corresponding FT pulse durations are 18 fs and 16 fs. The pulse profile obtained in the 2 mJ case is more sensitive to residual third-order phase that is not compensated by the chirped mirrors, leading to a more asymmetrical profile, a little further from the Fourier limited pulse profile than in the low-energy case. At 400 µJ a pulse duration of 26 fs FWHM is achieved at 4.5 bars which the actual limit pressure of the chamber before some leakage appears. Shorter pulse duration in the 20 fs range should be obtained at higher pressure between 5.5 and 6 bars.

The design of the MPC set-ups and the optimized operating conditions have been determined by different calculations based on simple models [6, 7] or a more sophisticated one [8]. The latter is based on the nonlinear laser pulse propagation equation in the slowly evolving wave approximation (SEWA). When using a perfect Gaussian temporal pulse profile for the calculations, we obtain a classical broadened spectrum with oscillations due to SPM as shown in black in Fig 3 b) for high-energy experimental conditions (2 mJ, 330 fs 1 bar of argon, concave mirrors with ROC= 300 mm, L= 595 mm, 27 passes).

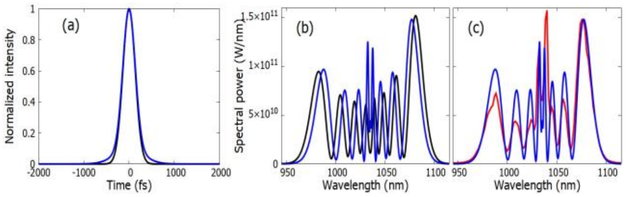

Fig. 3. (a) Initial 330fs temporal profile used for the spectra simulations in the ideal case (black line) and with degraded coherent contrast (blue line). (b) Respective calculated spectra obtained for a 2 mJ pulse propagating 27 passes in the MPC at 1 bar argon pressure. (c) Comparison between calculated (blue line) and experimental spectrum (red curve).

The calculated spectrum is larger than the experimental one and does not reveal the sharp peaks around 1030 nm observed experimentally (red line in Fig. 3c). They appear in the calculation when using a slightly degraded temporal pulse with lower coherent contrast but still with 330 fs FWHM duration (blue line Fig. 3a), which corresponds to the experimental situation. Comparison of the calculated and experimental spectra (Fig. 3c) shows that not only the spectral width and oscillations are perfectly reproduced by the code, but also the two sharp peaks around 1030nm. The calculated temporal profile at the MPC output is also in excellent agreement with the measured one.

Thus, we demonstrated sub-20 fs pulse compression at 80 W starting with an Yb-based laser delivering 330 fs pulses with energy between 0.8 and 2 mJ, using two very close MPC set-ups. Calculations and experimental measurements are in quantitative agreement for both MPC set-ups, whatever the experiments conditions. The numerical results also point out the prime importance of the temporal profile of the injected pulse on the shape of the broadened spectra.

1. T. Nagy *et al.* Adv. in Phys.: X **6**, 1845795 (2020).
2. L. Arias *et al.,* Opt. Lett. **47** (14) 3612 (2022)
3. C. Brahms and J. C. Travers, Opt. Lett. **48** (1) 151 (2022)
4. A.K. Raab et al., Opt. Lett. **47** (19) 5084 (2022)
5. L. Silletti et al., Opt. Lett. **48** (7) 1842 (2023)
6. A. Viotti *et al.*, Optica **9** (2), 197 (2022)
7. M. Hanna *et al.*, OSA Continum **4** (2), 732 (2021)
8. T. Brabec, and F. Krausz, Phys. Rev. Lett. **78** (17), 3282 (1997)