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Carrier-envelope phase stable few-cycle laser system delivering more than 100 W, 1 mJ, sub-2-cycle pulses

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Two-stage multipass-cell compression of a fiber–chirped-pulse amplifier system to the few-cycle regime is presented. The output delivers a sub-2-cycle (5.8 fs), 107 W average power, 1.07 mJ pulses at 100 kHz centered at 1030 nm with excellent spatial beam quality ($M^2 = 1.1$, Strehl ratio $S = 0.98$), pointing stability (2.3 µrad), and superior long-term average power stability of 0.1% STD over more than 8 hours. This is combined with a carrier-envelope phase stability of 360 mrad in the frequency range from 10 Hz to 50 kHz, i.e., measured on a single-shot basis. This unique system will serve as an HR1 laser for the Extreme Light Infrastructure Attosecond Light Pulse Source research facility to enable high repetition rate isolated attosecond pulse generation.

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Average power scaling of few-cycle laser systems has been one of the major efforts in ultrafast laser science recently [1,2]. In addition, for this short pulse duration, the carrier-to-envelope phase (CEP) stabilization is essential for certain applications, such as generation of isolated attosecond pules (IAPs) via high-harmonic generation [3,4]. The importance of these advanced sources is underlined by the Extreme Light Infrastructure Attosecond Light Pulse Source (ELI-ALPS), which is devoted to providing an unprecedented combination of pulse parameters. In particular, its high repetition rate (HR) beamlines are operated at 100 kHz and require CEP-stable operation with laser parameters well beyond the state of the art—1 mJ, 100 W, 6.2 fs for HR1 and 5 mJ, 500 W, 6 fs for HR2 [5,6].

In general, few-cycle pulses with multi-mJ pulse energies can be obtained via optical parametric chirped pulse amplification [7] or via post-compression approaches [8,9], with the latter achieving higher levels of average power [10,11]. Promising progress has been made using capillaries, where recently 318 W, sub-10 fs pulses were demonstrated [10]. However, further scaling to shorter pulses and higher average powers has been challenged by parasitic nonlinearities, ionization build-up effects, and associated thermo-optical effects [12,13]. Another approach is based on multipass cells (MPCs), which have seen enormous progress regarding average power scaling for attainable pulse durations of 20–30 fs [11]. Extending this approach further to the few-cycle regime encountered heating of metallic mirrors as a limiting factor [14,15]. Only very recently this was tackled by implementing enhanced silver mirrors on monocrystalline silicon substrates enabling 388 W of output power and compression of a beam sample (<1 W) to sub-7 fs [16].

Here, we demonstrate a successful combination of the latest MPC progress and CEP stabilization to define a new state of the art in few-cycle laser technology. Using a two-stage MPC approach allows one to compress 180 W, 1.8 mJ, 260 fs, 100 kHz pulses from an 8-channel coherently combined fiber-chirped pulse amplification system to 107 W, 1.07 mJ, 5.8 fs. The output is CEP-stabilized to 360 mrad rms, measured over the frequency range of [10 Hz, 50 kHz], i.e., a single-shot measurement of each and every pulse. This demonstration marks the highest compressed average power and shortest pulses from few-cycle MPCs and the first demonstration of a CEP-stable 100 W, 1 mJ-class, sub-2-cycle laser. The described system is being commissioned as an HR1 laser at the ELI-ALPS user facility in Szeged (Hungary).

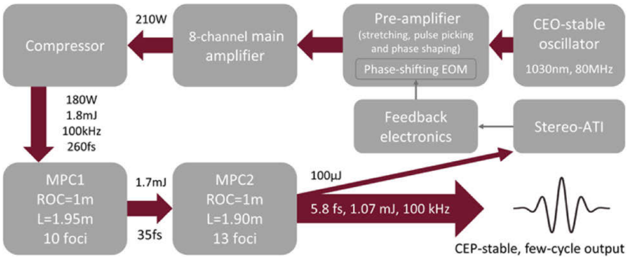

Fig. 1. Schematic setup of the HR1 laser system.

Figure 1 shows a schematic setup of the HR1 laser. The frontend is a carrier-envelope-offset (CEO) stabilized oscillator (Menlo Systems) operating at 1030 nm followed by a pre-amplifier system including temporal stretching and spectral phase shaping. Another key aspect is the implementation of CEP-preserving pulse picking [17], which allows one to obtain a 100 kHz, CEP-stable pulse train by picking every 800th pulse from the 80 MHz pulse train of the oscillator. After pre-amplification, eight spatially separated pulse replicas are generated and sent into the eight main amplifiers. Subsequently, the replicas are coherently re-combined and interferometrically stabilized to one another as described, e.g., by Klenke *et al.* [18]. Pulse compression is achieved in a dielectric-grating compressor, resulting in 180 W, 1.8 mJ, 260 fs pulses centered at 1030 nm used for the subsequent post-compression unit based on highly efficient MPCs.

The first compression stage (MPC1) comprises two radius of curvature (ROC) = 1 m mirrors placed at a distance of $L = 1.95$ m with 10 focal passes in total. MPC1 is filled with krypton at 1 bar to achieve the required spectral broadening. The pulse compression in MPC1 is done with dielectric chirped mirrors, providing a total group delay dispersion (GDD) of $-3150\,\mathrm{fs}^2$. Due to the use of highly reflecting mirrors, it can efficiently deliver 170 W, 1.7 mJ, 35 fs pulses, i.e., an overall efficiency of 94%. The second compression stage (MPC2) is similar to the one presented by Müller *et al.* [16], using ROC = 1 m enhanced silver mirrors placed at 1.90 m distance and producing 13 foci for nonlinear interaction in a 0.75 bar argon atmosphere. The pulse compression after MPC2 is obtained by broadband chirped mirrors with a total GDD of $-268\,\mathrm{fs}^2$ in addition to a mirror pair that compensates for 6 mm of fused silica. Before reaching the powermeter, 10% of the output is sampled by a broadband beamsplitter and used for CEP measurement and stabilization with a stereo-ATI pulsemeter (Single Cycle Instruments) and further analysis (beam quality, pointing, D-scan etc.).

The final output power after the mirror compressor and the 10% sampler is 107 W with an excellent stability over more than 8 hours of operation (STD of 0.1%, sampling period 1 s), as shown in Fig. 2.

Peak-to-peak energy fluctuations of 0.7% (single-shot measurement over 10,000 pulses) together with a superior pointing stability of 2.3 µrad were measured at the full output power of the system. In addition, the spatial quality of the output beam was analyzed by two different methods, firstly by measuring an $M^2 = 1.1$ (Gentec, Beamage-M2) and then the wavefront (Imagine Optics, Haso4 First). Both measurements confirm an excellent beam quality, and the wavefront measurement (Fig. 3) allows one to deduce a Strehl ratio of $S = 0.98$.

The pulse duration of the final output is measured by a commercial D-scan device (Sphere Photonics, D-cycle) that also allowed for dispersion optimization. Following the latter procedure, the algorithm yielded a compressed pulse duration as short as 5.8 fs (sub-2-cycle), as shown in Fig. 4 (root-mean-square retrieval error of 0.8%).

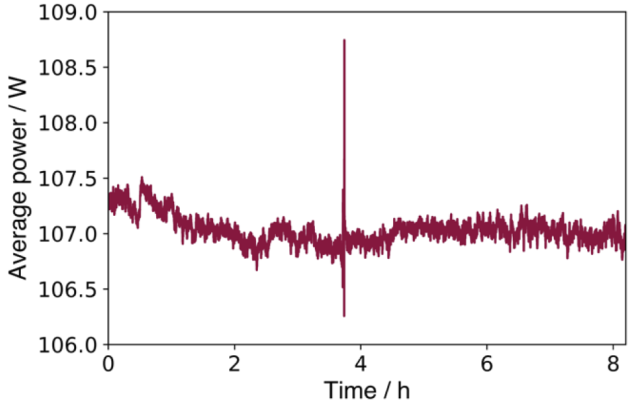

Fig. 2. Average power stability over 8 hours with 0.1% STD. The spike at 3.8 hours is caused by a required adjustment of the beam stabilization system parameters. Even though the average power seems to remain same during this event, it is also considered in the calculation of the stability value.

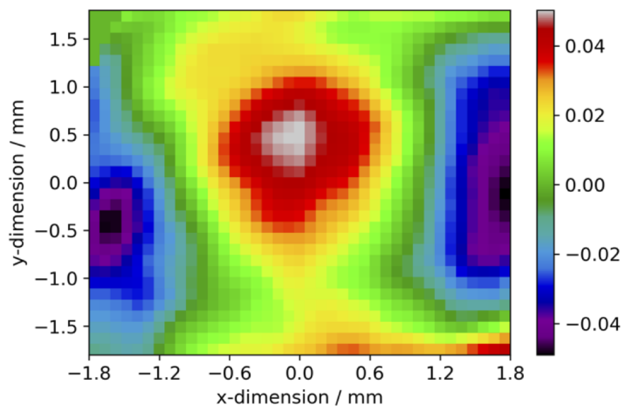

Fig. 3. Measured wavefront error of the final system output corresponding to a Strehl ratio of $S = 0.98$ (the scale of the color bar is in units of wavelength). The tilt and focus (spherical wavefront) have been removed. The remaining peak wavefront error is less than $\lambda/20$ (RMS error $\sim \lambda/40$).

One of the most crucial parameters of the laser system regarding its use in IAP generation is the stability of the CEP. As a first step it was demonstrated previously that the process of coherent combination does not affect the CEP-stability working up to 1 kW of average power from fiber amplifiers [19,20] and that post-compression after the fiber amplifiers generates CEP-stable few-cycle pulses at a HR [21]. In order to gain full insight into the noise properties of the system with respect to phase noise, the CEP of the 100 kHz pulse train is measured with a stereo-ATI pulsemeter. This method allows one to capture each and every shot of the pulse train and, therefore, is the most accurate and reliable characterization of this important parameter. The result of the CEP measurement is displayed in Fig. 5 in terms of asymmetry parameters [22,23]. With the CEO stabilization of the oscillator disabled, a so-called "phase potato" (light gray dots) shows an average radius of 0.7, which corresponds to

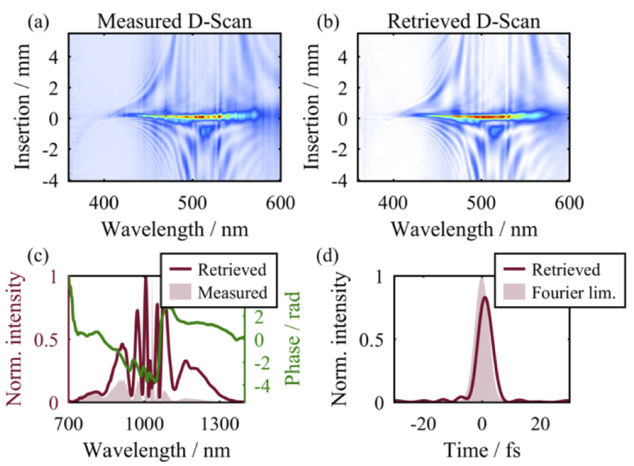

Fig. 4. The upper panels (a) and (b) show the measured and retrieved D-scan (root-mean-square retrieval error of 0.8%). (c) Measured and retrieved fundamental spectrum and the retrieved spectral phase. The narrowband peak in the measured spectrum is due to minor (<5%) uncompressed background from the chirped-pulse amplifier (CPA) that is expected to have no influence on the intended strong-field applications. (d) The reconstructed pulse shows a FWHM duration of 5.8 fs, which has been independently verified by the stereo-ATI pulsemeter.

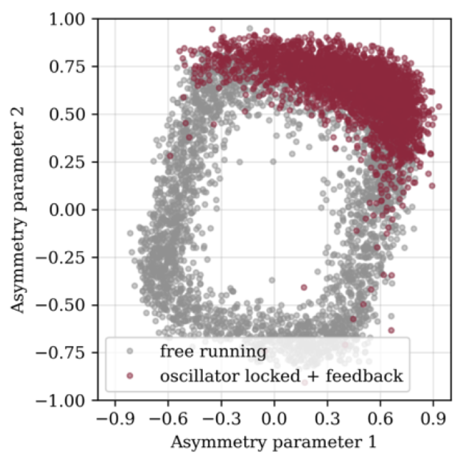

Fig. 5. Parametric asymmetry plot [22,23] of the stereo-ATI measurement at the final system output without (light gray) and with (dark gray) CEP-stabilization, i.e., with CEO locking of the oscillator, CEP-preserving pulse picking, and a feedback loop.

1.7 cycles (5.8 fs), validating the independently measured pulse duration [22]. The stabilization of the CEP is achieved with an active CEO-lock of the oscillator and an additional feedback loop from the stereo-ATI pulsemeter to a phase-shifting electro-optic modulator (EOM) in the frontend to correct for phase excursions in the CPA similar to Shestaev *et al.* [19]. With optimized feedback, the parametric asymmetry plot—the dark gray dots in Fig. 5—shows a clear narrowing of the CEP scatter, resulting in a stability of 360 mrad rms measured for the frequency range between 10 Hz and 50kHz, i.e., a pulse-to-pulse measurement without averaging.

In conclusion, a new state of the art in CEP-stable few-cycle laser technology is presented. It is realized by two-stage MPC compression of optical pulses delivered by a fiber-CPA system to yield 107 W, 1.07 mJ, 5.8 fs pulses at 1030 nm and a 100 kHz repetition rate with CEP noise of 360 mrad for Fourier frequencies of [10 Hz, 50 kHz]. The stability (average power—0.1%, peak-to-peak energy—0.7%, pointing—2.3 µrad) and beam quality ($M^2 = 1.1$, S = 0.98) are excellent. Further improvements to the CEP stability can be expected by improving the pre-amplifier system and the feedback loop. With these improvements in progress and upscaling of the MPCs, as discussed by Müller *et al.* [16], this concept paves the way for the ambitious parameters of the HR2 system, i.e., 5 mJ, 6 fs, CEP-stable output at a 100 kHz repetition rate in the near future.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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