TW) IR pulses. It should be noted, however, that the CEP stable construction of terawatt level OPCPA systems is technically challenging and the short pulse durations, as described in the paragraphs above, is not an obligatory precondition for production of IAPs anymore. The techniques to build terawatt level CPA systems on the other hand are well established and with the system presented in this paper a major step towards low repetition rate, even higher energy systems with very high quality CEP-stability has been demonstrated.

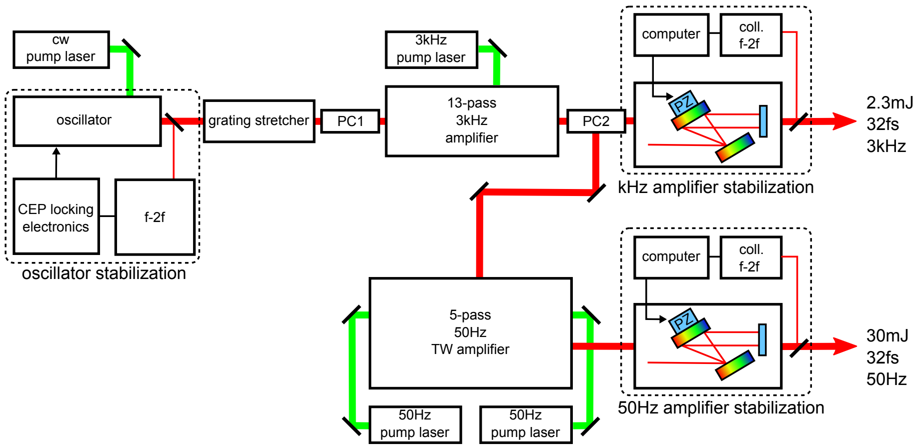

Fig. 1. Schematic drawing of the complete laser system including the elements for CEP-stabilization. The oscillator is stabilized using a piezo actuated tilt mirror [30] in combination with Menlo XPS f-2f interferometer and PLL-electronics. The output of both amplifier stages is stabilized by controlling the grating separation in the grating compressors [31–33]. The second amplification stage amplifies pulses at 50 Hz to the TW level while maintaining the same residual phase error as in the kHz-arm.

3. The laser setup

A schematic overview of the complete laser system is depicted in Fig. 1. It comprises two beam lines which will further be referred to as the kHz-arm and the 50 Hz-arm of the laser system. The kHz-arm consists of a commercial CEP-stabilized Ti:Sapphire based CPA system running at 3 kHz repetition rate (upper half of Fig. 1, KMLabs Dragon). The 50 Hz-arm is an additional power-amplifier seeded by amplified pulses of the kHz-amplifier which are picked at 50 Hz (lower half of Fig. 1) while the pulses at the remaining 3 kHz (every 60th pulse missing) further propagate through the original pulse compressor and can be used for experiments. Amplified pulses from the 50 Hz-arm are compressed in a separate grating compressor. Details of the implementation are discussed below.

The nJ seed-pulses are produced from a prism-based ultrashort pulse oscillator (KMLabs Griffin). An f-2f interferometer (Menlo XPS) including a photonic crystal fibre to generate the octave spanning spectrum and Menlo locking electronics (Menlo XPS-E) ensure CEP-stability by feeding an error signal back to a piezo actuated tilt mirror inside the oscillator cavity [3,30]. The resulting root-mean-square (rms) in-loop phase jitter is 104 mrad when measured over 40 milliseconds at 8 MHz bandwidth.

The CEP-stabilized oscillator seed pulses are stretched to approximately 220 ps in a grating based stretcher. After the pulses have been picked at a repetition rate of 3 kHz they are amplified in a single stage 13-pass cryogenically cooled Ti:Sapphire amplifier [34] which is pumped by a single diode-pumped 75W Nd:YLF laser (Photonics Industries, DM60). The

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amplified pulses reach an energy of 3.8 mJ, are routinely compressed to 30 fs and leave the compressor with an energy of 2.4 mJ. The CEP-stabilization of the kHz-arm was originally achieved by measuring the relative CEP with a commercial collinear f-2f interferometer and software (Menlo APS800) and feeding back to the grating separation using a piezo actuator inserted in the compressor translation stage [33]. In this configuration the rms CEP-jitter is around 300 mrad. The kHz-amplifier breadboard is rather compact and contains the stretcher, kHz-pulse-picker, kHz-amplifier and compressor.

To implement the power-amplifier a second pulse picker was inserted in the beam path before the compressor of the kHz-arm, picking the 3.8 mJ pulses at 50 Hz. The additional losses introduced to the kHz-arm by the pulse picker are only small and a pulse energy of 2.3 mJ after the kHz-compressor is maintained. There is also no measurable impact of the pulse picker on the CEP of the transmitted pulses.

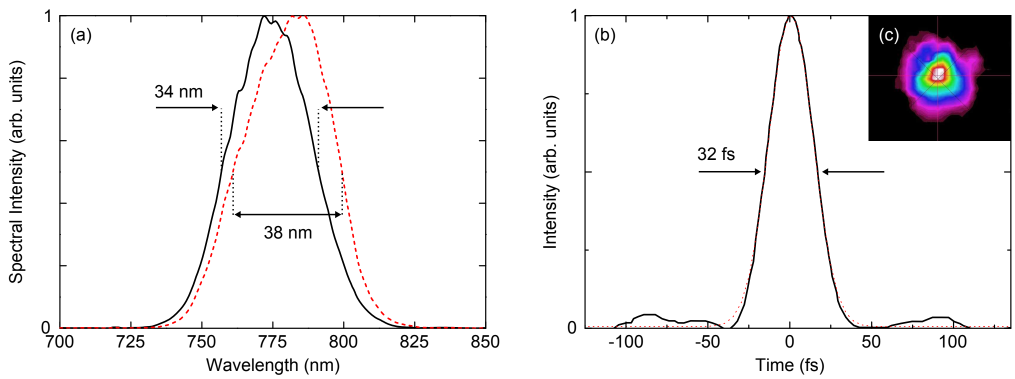

Fig. 2. Characteristics of the compressed 2 TW peak-power pulses. (a) The spectral profiles of the laser pulses before (black solid line) and after (dashed red line) amplification and their respective FWHM bandwidth. (b) The black curve shows the temporal pulse profile measured with SPIDER. The profile was fitted with a gaussian curve (dashed red line) which gives a FWHM duration of 32 fs. (c) The inset shows the spatial beam profile in the farfield as measured after a 1m focal length lens. It exhibits a slightly non-gaussian structure.

The picked pulses for the 50 Hz 5-pass power-amplifier are resized to a beam diameter of 4 mm. In view of the importance of the spatial beam quality in the 5-pass power-amplifier for achieving optimal energy extraction and a high final pulse energy, a pinhole spatial filter was inserted after the pulse picker. This comes at the expense of a reduction of the input energy into the power-amplifier to 1.4 mJ, however allows a higher final pulse energy from the amplifier crystal. The improved energy extraction is essential for the CEP-stabilization as will be clarified in the course of the article.

The 50 Hz power-amplifier is built up on a separate (90 x 180 cm^2) breadboard containing the pinhole setup, power-amplifier, compressor, two pump-lasers and an f-2f interferometer. For optical pumping two flashlamp-pumped Nd:YAG lasers are used (Litron, NanoTRL 320-50 dual head version). Each pump-laser can reach pulse energies of 160 mJ at a wavelength of 532 nm. The Ti:Sapphire crystal in the power-amplifier is water-cooled and pumped from both sides with each pump-laser respectively. At maximum pumping levels the amplified pulses can reach energies of >80 mJ. Routinely the output of the pump-lasers is slightly lower due to aging of the flash lamps and the crystal is effectively pumped with only around 120 mJ on each surface of the crystal. In this case the energies of the infrared pulses routinely reach 75 mJ indicating an optical efficiency of 31%. Thermal lensing inside the gain medium is compensated

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with several diverging lenses in between the individual passes.

Before compression, the 50 Hz amplified pulses are telescoped up to a 1/e diameter of 30 mm to prevent damage to the compression gratings. The spectral bandwidth after the kHz-amplifier is maintained in the 50 Hz power-amplifier with only a red-shift of the central wavelength by 10nm (see Fig. 2a). SPIDER (spectral phase interferometry by direct electric field reconstruction [35]) measurements indicated a pulse duration of 32 fs (see Fig. 2b). Due to the low individual efficiencies of the gratings (82%) the overall efficiency of the 50 Hz grating compressor is presently below 45%. The compressed pulses therefore only have an energy of 35 mJ corresponding to peak-powers of over 1.1 TW. By changing the gratings in the compressor energies exceeding 50 mJ should be easily feasible.

4. CEP-stabilization of the terawatt amplifier

In the course of the work the original Menlo APS f-2f setup of the kHz arm was rebuilt into a purely reflective setup to allow easier alignment and more flexible adjustment for higher fringe visibility by directly focusing the copropagating f and 2f beams [36, 37] onto the entrance slit of the spectrometer. A second equivalent system was set up to be used with the new 50 Hz amplifier stage. White-light generation was achieved by focusing the leaked light of a backside-polished mirror after the compressor into a 2 mm thick sapphire plate. The second harmonic of the long wavelength part of the white-light was generated in a 1 mm thick BBO crystal cut at a phase matching angle for 960 nm. The resulting spectral interference pattern which indicates a delay between the pulses of approximately 190 fs was detected using a USB-spectrometer (Thorlabs CS100).

At the same time the original Menlo software was replaced by a Labview-based homebuilt stabilization software, that allows online real single shot measurements as well as detailed settings for the PID feedback loop. The feedback in both compressors is achieved using a piezo actuators (Thorlabs Piezoelectric Actuator, Max Displacement 9.1 µm, 3.5 x 4.5 x 10 mm) inserted into the grating translation stages and the respective piezo controllers (Thorlabs MDT694A). The required voltages were directly written to the controller via the RS232 interface of the controller, allowing higher feedback frequency than in the original setup.

The first step to implement the CEP-stabilization of the 50 Hz-amplifier was to measure the isolated impact of the newly set up grating compressor [30], bypassing the 50 Hz power-amplifier and only running the oscillator CEP-stabilization. The recorded phase after the 50 Hz-compressor was compared against the phase measured after the original kHz-compressor. The fast phase jitter was comparable after both compressors, however the slow phase drifts measured behind the kHz-compressor were not visible in the measurements behind the 50 Hz compressor. We conclude therefore that most of the slow phase drifts of the kHz-system are accumulated only in the compressor setup whereas the stretcher has no measurable effect on the slow drift of the CEP. We suspect that this is due to thermal fluctuations as well as direct thermal load on the kHz-compressor. The fluctuations are not visible in the 50 Hz-compressor as the thermal load without pumping is negligible.

Taking into account the influence of thermal drifts introduced by the amplifier and the pump-lasers, the 50 Hz-amplifier was set up in such a way as to leave ample room in between the individual components. Additionally, compressor and f-2f interferometer were separated by vertical metal walls inside the amplifier housing and all walls were covered with foam to prevent acoustic noise from coupling into the CEP. The two pump-lasers were effectively decoupled from the breadboard by placing 25 mm thick sorbothane sheets beneath them. However it turned out that the pump-lasers initially introduced strong thermal fluctuations causing CEP jumps which could not be compensated by the slow feedback loop. Accordingly the pump-lasers were as well separated with metal walls from the amplifier section and it was ensured that there was

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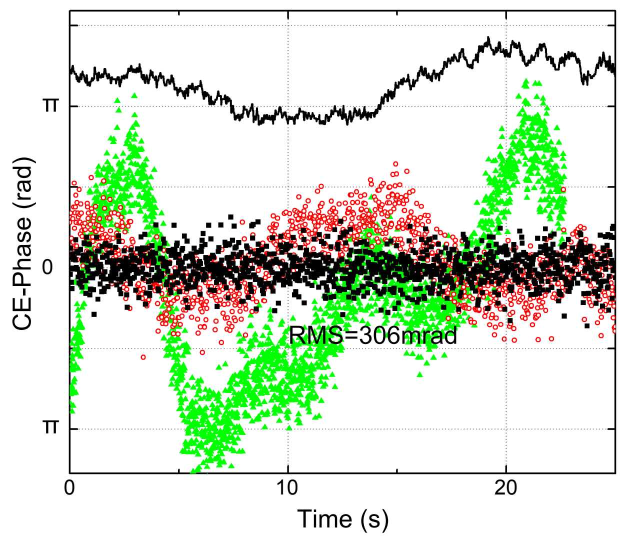

Fig. 3. Short term CEP measurements showing the stabilized (black dots) phase and the necessary compensating phase (black line) that is introduced in the grating compressor. For comparison typical cases of the free-running CEP evolution in the kHz arm (green triangles) and in the 50 Hz arm (red circles) are depicted as well. These measurements were not taken simultaneously and therefore one cannot draw any conclusions on correlation between the free running evolution in the two arms.

enough air circulation in the pump-laser section to remove the excess heat from the rest of the breadboard housing.

Figure 3 shows the CEP-drift for the amplified 50 Hz-arm in the stabilized case (black squares) and in the free-running case (red circles). For comparison a trace of the kHz-arm in the free running case is also plotted (green triangles). In both free-running cases, only the oscillator CEP-stabilization was active. In agreement with the before mentioned observation, the 50 Hz-arm shows a slow drift with significantly lower amplitude compared to the kHz-arm. This is due to the direct thermal load on the compressor gratings, as mentioned before. In the kHz-compressor the dissipated heat is by a factor 2 - 3 higher than in the compressor after the TW-amplifier. Additionally the thermal expansion coefficient of the copper grating substrates used in the kHz-compressor ($17 \cdot 10^{-6}$/°C) is significantly higher then those of the BK-7 gratings ($7 \cdot 10^{-6}$/°C) used in the TW-compressor.

In the first amplification attempts the optical efficiency was rather low with values of around 20-25%. As a result the pulse-to-pulse energy fluctuations of the amplified pulses were large. This can easily translate into instabilities in the CEP measurement mostly during the strongly non-linear white-light generation process [38, 39]. As a result the measured CEP-stability only reached values of above 700 mrad (see Fig. 4 blue trace). In order to achieve a better stability of the pulse energy and therefore also of the CEP measurement, we adjusted the amplifier to be operated at higher saturation levels. At efficiency levels of 31 % the phase-jitter is reduced by a factor of more than two to values around 300 mrad in single pulse measurements. Results of a long term measurement are shown in Fig. 4. The rms-stability of both pump-lasers is 0.56% and of the amplified pulse in this configuration is 0.6%.

Nonetheless even at this value the achievable CEP stability appears to be limited by shot noise resulting from the low photon numbers in the relevant spectral ranges produced in the white-light generation process. This assumption is supported by two facts: First the histograms plotted

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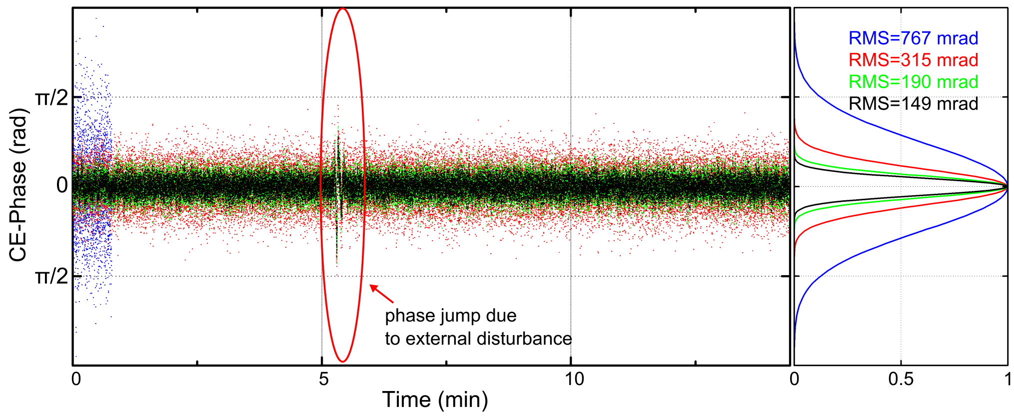

Fig. 4. Measurement of the CEP stability over an extended time interval. The red curve shows the CEP single shot CEP measurements of the 50 Hz TW-amplifier in the optimal configuration. The dots in green and black show the same measurement when averaging over three shots and five shots respectively. Histograms for all three cases are shown on the right with the respective rms error values of 315 mrad, 190 mrad and 149 mrad. For comparison a short measurement of the phase jitter is included in the case of low extraction efficiency (21%) (blue dots).The respective rms value is 767 mrad.

in Fig. 4 and the resultant rms-values follow almost perfectly a Gaussian statistic, indicative for a white noise limitation. If however the oscillator would be a limiting factor at this point, one would expect a non-Gaussian statistic [40]. Second, the analysis of the frequency spectra of the residual phase error (not plotted here) revealed similar indications. A clear reduction of the slow modulations up to a frequency of 0.3 Hz was visible comparing the free-running against the stabilized case. Higher frequencies however were already covered by the average shot noise level.

The high shot noise level finds its origin in the extremely low spectral densities in the 2f arm of the interferometer. Considering that the white-light generation in the Sapphire plate is limited to only a few microjoule of input energy, the effectively detected photon number N in the frequency-doubled part of the spectrum might be as low as 10^4, taking into account conversion efficiency into the IR, the doubling efficiency and losses in the spectrometer. The achievable phase resolution between consecutive laser pulses is then limited to a value of $\Delta\phi_{CE} = \pi/(N/2)^{1/2}$ [41], i.e. values between 40 - 50 mrad. These numbers however hold only for a perfect detection system. In the case of a fast CCD chip the resultant value could be higher by up to one order of magnitude [40] and thus lie at similar levels as those measured in our f-2f setup.

The situation could be tremendously improved by increasing the photon numbers in the relevant frequency range. Using super-continuum generation in noble gases would allow input energies in the mJ range with high conversion efficiencies in the super-continuum generation process. A realistic increase in the relevant photon number by a factor of 10 or more would hence improve the shot noise by more than an order of magnitude. With the laser system presented in this chapter, the pulse energies to run a noble gas filled fibre setup which would generate the necessary white-light, would only amount to 2 - 3 % of the total output energy of the system, and should therefore be the next implementation step.

Even at shot noise limitations the final CEP-stability of the system is still strongly dependent on external environmental influences. Especially mechanical vibrations seem to play a major role, i.e. the difference of rms-error values of the CEP can be as high as 150 mrad when com-

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paring measurements taken during the day and after working hours. Since the laser systems are supplying experimental setups that are not connected to the optical table, floating the table is not an option. We expect that the rms value of the system could still improve when moving to a more stable environment.

It should be noted that while most publications on CEP results of amplifier systems are based on averaged measurements, the values presented in this paper are real single shot measurements at the full repetition rate of the laser system. As was shown by [41], single shot measurements at the full repetition rate of the laser system are necessary to determine the real phase stability of a system. The demonstrated rms-values of the residual phase jitter are therefore excellent values and rank among the best values measured so far for such laser systems [27,29,41,42]. To make the results comparable with other published data, the long term single shot measurement in Fig. 4 is also shown for cases when a moving average over three and five pulses was applied. As expected, the rms-value of the phase jitter in these cases is reduced dramatically to 190 mrad and 149 mrad respectively.

5. Conclusion

In this article we present a terawatt level femtosecond laser system, which is perfectly suited for the generation of IAP using the techniques reviewed in the first part of the paper. The demonstrated pulse properties of the amplified pulses are a pulse duration of 32 fs and a peak-power of 1.1 TW at 50 Hz repetition rate. It was shown that CEP-stabilization in this CPA system can be achieved with a residual phase jitter which competes with the best stabilization results published so far.

To our knowledge the presented results show the highest pulse energy reached for CEP-stabilized femtosecond pulses to date, and opens up the possibility to produce IAPs with unprecedented photon fluxes. This is an important step towards experimental conditions that allow experimental researchers to perform XUV-XUV pump-probe experiments.

Further it paves the way towards even more energetic driver pulses with stable CEP. Nowadays CPA systems with repetition rates in the 10 Hz regime and several Joule of pulse energy are commercially available. From the demonstrated measurements we conclude that scaling to higher energies should be straight forward, as long as the pulse repetition period is short compared to the slow thermal fluctuations introduced in the compressor and the pulse-to-pulse energy instabilities can be maintained at a low level.

The availability of high pulse energies might additionally promote the use of super-continuum generation in fibres for the use with the f-2f interferometer. This could potentially allow a significant increase in the phase sensitivity in the f-2f measurement and therefore should be further investigated in the future use of such a laser system.

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