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Status of the Petawatt Field Synthesizer — pump-seed synchronization measurements

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Abstract. The Petawatt-Field-Synthesizer (PFS) project at the Max-Planck-Institut für Quantenoptik (Garching), aims at combining few-cycle pulse durations with petawatt-scale peak powers by using short pulses (on the few-ps scale) for both seeding and pumping an optical parametric chirped pulse amplification (OPCPA) chain. Such a short-pulse pumped OPCPA approach imposes very strict demands on the synchronization between the seed and the pump pulses, i.e. the timing jitter between the pulses has to be below the 100 fs-level. We report on recent progress on the development of the PFS system, in particular about the investigation of the pump-seed timing jitter. We have identified the grating stretcher/compressor setup of the pump laser chain as the main source of a temporal instability of about >200 fs rms and propose ways to eliminate this in order to allow for first short-pusle pumped OPCPA experiments.

Keywords: High-power laser, Short-pulse OPCPA, Diode-pumped CPA pump source, Temporal synchronization
PACS: 42.65.Yj, 42.60.By, 42.55.Xi

INTRODUCTION

Optical parametric amplification (OPA) has opened a path towards a completely new regime of generating ultrashort, high-power laser pulses, that reaches well beyond the limits of conventional laser technology in term of achievable peak intensities [1]. In combination with the chirped-pulse amplification (CPA) principle [2] (i.e. OPCPA) few-cycle pulses and pulse energies of several tens of Joule have already been achieved [3, 4, 5, 6], however, not yet simultaneously.

The Petawatt Field Synthesizer (PFS), currently under construction at the Max-Planck-Institut für Quantenoptik (Garching, Germany), aims at delivering wave-form controlled, few-cycle laser pulses with petawatt-scale peak power [7]. The PFS design is based on a modified scheme of OPCPA, where short pulses (of the order of a few ps) are used for both seeding and pumping the amplification chain. This is currently the only available concept for combining few-cycle pulse durations with petawatt-scale peak powers, which also constitutes the proposed architecture for the pan-european Extreme Light Infrastructure (ELI) frontend [8].

In order to achieve the goals of PFS, the nonlinear crystal for the parametric amplification chain has to support both an ultra-broad amplification bandwidth and the required pulse energies by having a sufficiently large aperture. Therefore, in the PFS design, DKDP is chosen as the nonlinear medium, which calls for a broadband seed pulse in the near infrared (NIR), i.e. in the spectral range of 700 – 1400 nm, for the broadest

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possible gain bandwidth. In addition, using thin crystal thicknesses allows to further increase the amplification bandwidth, while the gain can be kept at a reasonably high level by high-intensity pumping through short pump-pulse durations (on the ps level). This short-pulse pumped OPCPA scheme imposes stringent demands on the required pump source, which is designed to deliver pulses of 1 ps duration at 515 nm with a total energy of 15–20 J at a repetition rate of 10 Hz. Such a pump source is not commercially available and therefore represents a challenge for development on its own right. It is based on the CPA concept using diode pumping and Yb:YAG as the gain material.

The technique of few-ps OPCPA possesses immense potential for generating high contrast pulses due to the short, ps-scale time window for the parametric fluorescence, but this in turn demands a very accurate and stable synchronization between the pump and seed pulses. A timing jitter of few-100 fs can result in a significant change in the amplified spectrum and hence variations in the compressed-pulse duration on each shot. Therefore a common frontend has been developed for generating the broadband OPCPA seed and an optically synchronized seed pulse for the pump-laser chain [9]. The schematic layout of the PFS system is shown in Fig. 1, indicating the common frontend, the stages of the pump-laser CPA chain and finally the subsequent stages of the main short-pulse pumped OPCPA chain. More details on the synchronized seed generation and the frontend architecture can be found in [9]. Details on preliminary stages of the pump-laser chain are described in [10, 11, 12]. The general concept and the OPCPA design are described in [7].

In this work we focus on the issue of the pump-seed synchronization, representing a crucial prerequisite for setting up the short-pulse pumped parametric amplifier stages. We first describe the method used for our shot-to-shot characterization of the relative timing between the pump and the seed pulses, i.e. the timing jitter between them. We then present a series of measurements that allowed us to identify the source of large timing fluctuations, and finally we discuss ways for eliminating these.

GENERATION OF PUMP AND SEED PULSES

The high demand on the synchronization between the pump and seed pulses imposed by the short-pulse-pumped OPCPA scheme necessitates optical synchronization for pump and seed pulses, by deriving both from a common source. As indicated in Fig. 1 the broadband seed pulse is generated by using a cascaded spectral broadening technique, while a photonic crystal fiber (PCF) is used to upshift part of the oscillator spectrum to 1030 nm, which is appropriate for seeding the pump laser chain [9].

However, before the parametric amplification of the broadband seed pulses can take place, the pump pulse has to pass through the entire pump-CPA chain as indicated in Fig. 1. After stretching, the amplification in the pump-laser chain currently takes place in an Yb:glass regenerative amplifier followed by a multipass amplifier based on Yb:YAG, both of which are diode pumped. These two stages allow for the generation of pulses with 300 mJ energy and an amplified bandwidth of 3.5 nm at 10 Hz. The details of these amplifiers are described in Refs. [10, 11, 12]. Finally, the amplified pulses are recompressed to $\sim$ 1.4 ps in a Treacy-type pulse compressor with a grating separation of $\sim$ 6.5 m with an overall throughput of 65%.

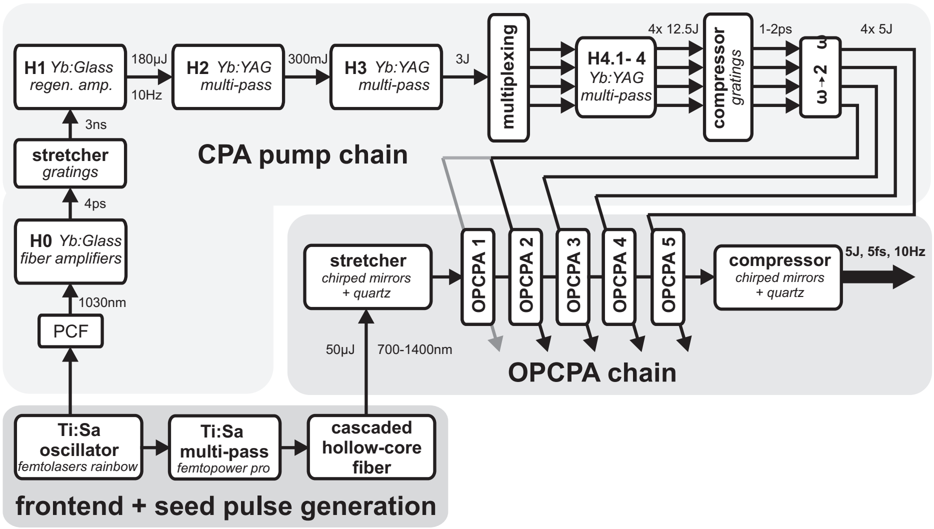

FIGURE 1. Schematic layout of the PFS system (reproduced from [7]). The seed pulses for both the main OPCPA chain and the pump-laser CPA chain are derived from the common master oscillator and are therefore optically synchronized.

This long path through the pump-laser chain results in $> 1\ \mu s$ of total optical delay between the OPCPA pump and the seed at the position of the first OPCPA stage. In order to overcome this delay, different pulses from the “master oscillator” of the common frontend are selected for the pump and the seed chains before being combined in the OPCPA stage. In this scheme the sources of possible timing fluctuation between the two pulses can be the finite stability of the repetition rate of the master oscillator, temperature drifts, air turbulences and mechanical vibrations of optical components over this rather long optical path of the pump pulse.

TIMING JITTER MEASUREMENT

In order to quantify the level of synchronization in the above described setup we performed single-shot measurements of the relative timing between the pump and the seed pulses. For this purpose we used the so-called spectral gating technique [13], which is schematically depicted in Fig. 2. The relative arrival time of the pump and the seed pulses is converted into spectral information by generating the sum frequency (SFG) signal between the short pump pulse and a linearly chirped, long reference pulse in a BBO crystal. We used the compressed ~ 1.4 ps pump pulse before it was frequency doubled, i.e. at 1030 nm. Our reference pulse was split off from the common frontend before compression and spectral broadening. It therefore had a duration of ~ 8 ps (FWHM) and a bandwidth of ~ 60 nm. We can safely assume that the additional compression and broadband seed generation does not introduce significant additional timing instabilities,

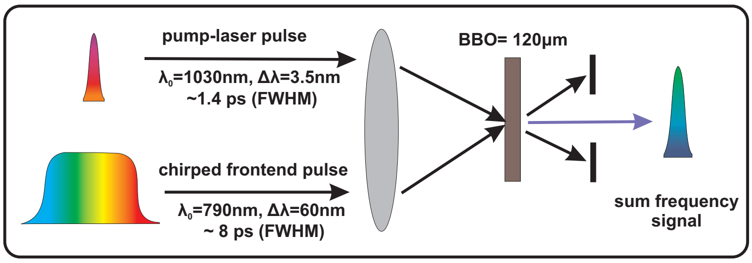

FIGURE 2. Schematic picture of the spectral gating technique [13]. The spectrum of the sum frequency signal between the short pump pulse and a long, chirped reference pulse is measured. The relative time of arrival between the two pulses is transformed into spectral information which can be resolved with a resolution of ∼ 10 fs by the spectrometer.

since the optical path difference is negligible compared to that of the pump pulse. By monitoring the spectrum of the SFG signal using a high-resolution spectrometer the relative arrival time of the two pulses can be deduced from the peak position of the spectral distribution. This scheme is insensitive to pointing fluctuations (for spatial-chirp free pulses) and shot-to-shot energy changes of the test pulses. The resolution of the technique in our case is ∼ 10 fs, which is given by the spectrometer resolution (0.15 nm for Avantes AvaSpec 2048) in combination with the accuracy of the determination of the peak position of our spectral distribution.

RESULTS AND DISCUSSION

Our findings are summarized in Fig. 3. The fluctuation of the relative timing between pump and seed are show in Fig. 3 a). Here the pump beam is stretched, fully amplified in the regen and the multipass amplifier and subsequently compressed. For this measurement no precautions were taken to reduce air fluctuations within the boxes covering the entire system, especially the compressor. We find that the timing jitter in this case is ±400 fs, which is clearly unacceptable for proceeding with the short-pulse pumped OPCPA experiments. Fig. 3 b) shows the same pass through the amplification chain after the installation of beam tubes in the compressor that reduce air turbulences along the long propagation distances of the beam. From our measurement over ∼ 5 minutes, we can clearly see that there are two separate components to the remaining timing jitter: a shot-to-shot variation of ±70 fs superimposed on a slow temporal drift of ±200 fs. From the Fourier transform of this jitter measurement (shown in Fig. 3 c)) we can determine the frequency at which the slow temporal variation takes place to be <0.1 Hz.

In order to determine the source of this rather large but slow temporal oscillation, we studied the effect of the different components of the CPA pump-laser chain. First, we investigated the impact of the long delay in the regen by bypassing the stretcher-compressor setup and amplifying the unstretched pulses in the regen to a low power level. The relative timing was then measured between the frontend and the pulses amplified in the regen in case when i) the same pulses, and ii) different pulses with

$> 1\mu s$ delay were selected from the master oscillator for both chains. Fig. 3 d) shows the resulting timing jitter, which in both cases is reduced to the few-10s of femtoseconds level. This corresponds to the resolution limit of our measurement setup, but is clearly well below our needs for the short-pulse pumped OPCPA. We can therefore conclude that in spite of the long delay in the regen, this is not the origin of the large timing oscillations but that they arise from the stretcher-compressor setup. We believe that the mechanical instabilities and air fluctuations along the long propagation distance contribute strongly to this timing instability.

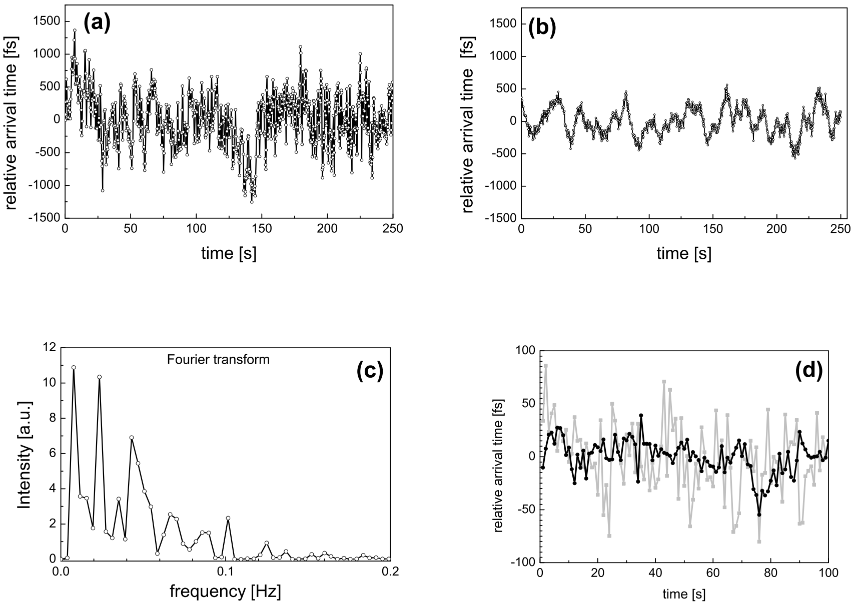

FIGURE 3. Results of timing jitter measurements using the spectral gating technique (cf. Fig. 2). a) Pump pulse passes through entire CPA chain: ±400 fs timing jitter. b) Pump pulse passes through the entire CPA chain with beam tubes in the compressor: timing jitter consists of ±70 fs shot-to-shot fluctuation and ±200 fs slow oscillation. c) Fourier transform of b) showing the highest frequency of the slow oscillation around 0.1 Hz. d) Timing jitter when stretcher/compressor are bypassed: ±14 fs when the same pulses are used from the master oscillator; ±33 fs with $> 1\mu s$ delay.

Having identified the stretcher/compressor setup as the main source of the pump-seed timing jitter, we will now be able to systematically eliminate this instability in order to ensure a stable operation of the short-pulse OPCPA chain. Firstly, guiding the beam in beam tubes wherever possible seems to already reduce the jitter notably by diminishing the air turbulences along the propagation path. However, if this proves to be insufficient in the future, enclosing the entire stretcher/compressor in air-tight containers flooded by helium or even in vacuum chambers is expected to eliminate these instabilities altogether. In addition, since the slow drift takes place on a time-scale of a few seconds which is much longer than the repetition rate of the system (i.e. 10 Hz), an active stabilization system could easily correct for this large amplitude, slow fluctuation.

Such a system is currently being developed. The remaining shot-to-shot fluctuations are below the 100 fs level and are therefore sufficiently low for carrying out the OPCPA experiments.

CONCLUSIONS

In conclusion, we have quantitatively investigated the level of timing synchronization between the pump and seed pulses of the PFS system, which is currently under development at MPQ. Using the spectral gating technique we demonstrated that the stretcher/compressor setup is the source of a large-amplitude drift on the time scale of a few seconds. This finding was contrary to our expectations that the large delay generated in the regenerative amplifier is the cause of the observed timing fluctuations. In order to prepare the system for first short-pulse pumped OPCPA experiments we propose to eliminate these large timing instabilities by appropriate housing of the beam inside the stretcher/compressor setup as well as an active stabilization system which eliminates the slow drift at a repetition rate of 10 Hz.

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