An optical parametric chirped-pulse amplifier for seeding high repetition rate free-electron lasers

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Abstract
High repetition rate free-electron lasers (FEL), producing highly intense extreme ultraviolet and x-ray pulses, require new high power tunable femtosecond lasers for FEL seeding and FEL pump-probe experiments. A tunable, 112 W (burst mode) optical parametric chirped-pulse amplifier (OPCPA) is demonstrated with center frequencies ranging from 720–900 nm, pulse energies up to 1.12 mJ and a pulse duration of 30 fs at a repetition rate of 100 kHz. Since the power scalability of this OPCPA is limited by the OPCPA-pump amplifier, we also demonstrate a 6.7–13.7 kW (burst mode) thin-disk OPCPA-pump amplifier, increasing the possible OPCPA output power to many hundreds of watts. Furthermore, third and fourth harmonic generation experiments are performed and the results are used to simulate a seeded FEL with high-gain harmonic generation.

1. Introduction

Free-electron lasers (FEL) based on large scale linear electron accelerators are sources of highly intense extreme ultraviolet and x-ray radiation [1]. In particular, the development of high repetition rate FEL requires new optical laser developments to meet the needs of laser-induced FEL seeding and for lasers used in FEL pump-probe experiments. Conventional copper accelerating cavities operate at tens to hundreds of hertz, but superconducting (SC) cavities, developed for example at DESY (Hamburg, Germany) [2], allow a much higher repetition rate of up to few megahertz: FLASH at DESY has a maximum repetition rate of 1 MHz within a burst structure (electron bunch train) of 800 μs at 10 Hz [3, 4]. Future linear accelerator designs, for example, the LCLS-II FEL at SLAC (Menlo Park, USA), plan a SC linear accelerator capable of a continuous repetition rate of up to 1 MHz [5]. This presents major challenges for the design and operation of laser–seeded FELs and FEL pump-probe lasers operating in both burst and continuous mode. At lower repetition rates, conventional Ti: sapphire lasers are currently used as a FEL pump-probe laser, for example at FLASH in DESY [6], or for laser induced FEL seeding at, for example, FERMI FEL-1 (Trieste, Italy) [7]. The future requirements of a tunable, high repetition rate laser with sufficient pulse energy can be met with optical parametric chirped-pulsed amplification (OPCPA).

In the last years there has been remarkable progress in high average power OPCPA systems. Currently, high repetition rate and high average power OPCPAs have been demonstrated at an average power of 15 W [8, 9] and 22 W [10]. In burst operation, 38.5 W was achieved within a burst structure similar to FLASH [11], and 34 W constructed for the European XFEL (Hamburg, Germany) [12]. OPCPA has a number of advantages compared to Ti:sapphire lasers. OPCPA is scalable to many hundreds of watts (in continuous mode) [13], amplifies a larger bandwidth and is not limited by gain narrowing [10, 14], and is a wavelength tunable amplifier. Additionally,
because OPCPA has a very large single pass gain and thereby a relatively short signal path length, timing jitter is often smaller compared to the long-path length required from Ti:sapphire amplification, requiring a regenerative amplifier with a path length of more than 100 m.

These high power OPCPAs are made possible by recent developments in Yb-doped solid-state laser amplifier technologies (for example, fiber [15], Innoslab [16] and thin-disk [17]) with picosecond to sub-picosecond pulse durations, demonstrating the potential to reach kilowatts of average power at 1030 nm for OPCPA pumping. In the pump system developed here, a fiber amplifier is used to bring pJ-nJ pulse energies into the tens of μJ-level with powers between 10–50 W; thereafter booster amplifiers are necessary to bring power levels into the kilowatt-range, consisting of Innoslab amplifiers and/or thin-disk multipass amplifiers [17]. Recently, thin-disk multpass amplifiers have demonstrated burst powers up to 14 kW [18].

FELs distinguish themselves not only by the type of linear accelerator, but also by the FEL process. The FEL can be ‘seeded’ by the shot noise radiated from an electron beam as it passes through an undulator. This process is called self-amplified spontaneous emission (SASE) [19]. Therefore, FEL pulses resulting from the SASE process suffer from fluctuations in pulse energy, pulse duration, spectral and temporal coherence, and arrival time. These parameters can be greatly improved by seeding the FEL with an external seeding laser. Seeding improves the longitudinal coherence, allows direct optical synchronization from the seeding to the pump-probe laser and improves the shot-to-shot stability, compared to the SASE process.

There are several methods to seed an FEL [20]. Direct seeding, where the seeding wavelength is the same as the FEL wavelength, was first shown at 160 nm [21], and later at 38.2 nm [22], using a high harmonic generation (HHG) source. Another promising approach is high-gain harmonic generation (HGHG). In this case, the seeding laser wavelength is a sub-harmonic of the (HHG) source. Another approach is high-gain harmonic generation (HGGH). In this case, the seeding laser wavelength is a sub-harmonic of the final undulator radiation [23, 24]. This method is reliable and forms the basis of the user facility at the FERMI (Trieste, Italy) [7, 25]; however, to reach lower FEL wavelengths, cascaded HGHG [26] or echo-enabled harmonic generation [27] should be considered. For all these examples, Ti:sapphire lasers are currently used as the driving laser.

To take full advantage of FEL seeding, the laser source should be wavelength tunable. Additionally, future FEL users request ever shorter FEL pulses. As a compromise between obtaining sufficient seeding pulse energy and pulse duration, we chose a seeding pulse duration of 30 fs, since shorter pulses would reduce the efficiency of the third harmonic generation (THG) from the OPCPA. With an OPCPA tunable range from 720–900 nm, HGHG seeding will be shown to cover the range from 26–43 nm.

The outline of this paper is organized as follows. We first present the design and results of a tunable, 112 W OPCPA seeding laser, which provides long-term stable operation. Thereafter we present various THG and fourth harmonic generation (FHG) schemes to generate seed pulses for HGHG. Finally, these results are used as input to simulate a possible seeded HGHG setup at FLASH2 (DESY).

2. OPCPA setup and results

An OPCPA combines two amplification methods: chirped pulse amplification (CPA) and optical parametric amplification (OPA) [28]. In CPA, the signal pulses are first temporally stretched to obtain lower signal intensities before being amplified; thereafter the signal pulses must be compressed. This technique lowers the peak intensity during the amplification process in order to avoid nonlinear propagation effects and material damage issues. In OPA, the energy of the pump wave ($\omega_p$) is transferred, via a second-order nonlinear effect within the gain material, into signal ($\omega_s$) and idler ($\omega_i$) waves. Thereby, energy conservation is maintained between the three waves ($\omega_i = \omega_p - \omega_s$) and therefore energy is not stored in the gain material. In comparison, Ti:sapphire, where the pump energy is stored in the gain material through population inversion, has a quantum defect of 34%, and the resulting energy difference goes into heating of the gain material. This is the critical advantage, which allows an OPCPA to operate above 112 W without additional cooling of the nonlinear OPA crystals.

2.1. Frontend and OPCPA-pump amplifier

The optical setup of the 3-stage OPCPA is shown in figure 1. As the frontend, a broadband Ti:sapphire oscillator is used (Venteon Pulse:One OPCPA seed), delivering 2.5 nJ pulses at a repetition rate of 108 MHz, with a spectral bandwidth >350 nm (at –10 dBc). Because this oscillator has a broad spectrum, it is possible to seed both the Yb-based pump amplifiers at 1030 nm, as well as the broadband OPCPA stages ranging from 650 nm to 950 nm. This frontend is an all-optically synchronized seeder, minimizing the jitter between OPCPA-signal and OPCPA-pump pulses at the parametric amplification stages. In addition, the oscillator is fitted with two piezoelectric-controlled mirrors for optical synchronization to the FEL [29].

The OPCPA-pump is a CPA system. The pulses are first amplified in a preamplifier system, delivering pulses with a bandwidth of 6.8 nm (FWHM), at a power of 1.9 mW at 2 MHz. Thereafter, the pulses are stretched to
2.27 ns (FWHM) in an Öffner-type stretcher. The output is further amplified by a three-stage fiber system, consisting of one double clad fiber amplifier and two large mode area photonic crystal fiber amplifiers to an average power of 10 W. For further details see [30].

The booster stages consist of a 500 W multipass Innoslab amplifier and two additional 500 W single-pass Innoslab stages (AMPHOS). The pulses are then compressed with an efficiency of 86% and have a final pulse energy of 12.5 mJ at a pulse duration of 1.1 ps (FWHM). Finally, a 4 mm LBO crystal delivers a final pulse energy of 6.4 mJ and a pulse duration of 920 fs at 515 nm, resulting in a conversion efficiency of 51.2%. Pulse durations were measured with an intensity autocorrelator (APE: Pulse Check 50).

2.2. High power tunable OPCPA dispersion/pulse management

For broadband OPCPA, the signal pulse duration ($\tau_s$) must be stretched to match the pump pulse duration ($\tau_p$), where $\tau_s \leq \tau_p$. A high power OPCPA example is given in [11], where the signal was stretched with a fused silica prism pair together with a spatial light modulator, thereafter the pulses were amplified to pulse energies of 1.4 mJ with a spectral bandwidth supporting sub-7 fs pulse duration at 27.5 kHz within a burst structure of the FLASH. For a tunable system, the signal pulse duration must be stretched well beyond the pump pulse duration ($\tau_s \gg \tau_p$). Using a delay between the pump and the signal pulses ($d_{sp}$, figure 1), the pump pulse amplifies a selected temporal region of the signal, thereby selecting a center frequency. The signal is stretched using a SF57
prism pair with two adjustable dimensions \((l_p\text{ and } p_p, \text{figure 1})\). To achieve approximately 30 fs pulses across a broad spectrum, the degree of pulse stretching is adjusted corresponding to a new center frequency varying \(l_p\) (\(\text{figure 2(a)}\)). Further fine adjustment of the prism pair to reduce third order dispersion is achieved varying \(p_p\). A number of example spectra after amplification with center frequencies ranging from 720 nm to 900 nm is shown in \(\text{figure 2(b)}\). In practice, the center-of-gravity (COG) of the amplified output spectra is used as feedback to lock the center frequency by regulating the delay \(d_{sp}\). This regulation also compensates for slow timing drifts between the signal and the pump; for more details of this method see [11]. Presently, \(l_p\) and \(p_p\) are not under computer control, but need only to be fixed once in a repeatable way for each center frequency. Finally, the amplified pulses are compressed close to their Fourier-limit in a fused silica glass, where the amount of glass can be varied to compensate for different dispersion (\(\text{figure 3}\)).

2.3. Three-stage OPCPA results

The three-stage non-collinear OPCPA consists of three \(\beta\)-barium borate (BBO) crystals of length 6, 4 and 2.2 mm. In the first OPCPA stage, a 6 mm BBO is pumped with a fraction of the pump of 0.47 mJ with intensity of 28 GW cm\(^{-2}\). The signal beam diameter is with \(\times 2.9 \times 1.7\) mm\(^2\) (1/e\(^2\)) slightly bigger than the pump size, in order to reduce the impact of spatial beam fluctuations in the OPA process. The signal pulses are amplified from about \(~0.5\) nJ to \(25\) \(\mu\)J, corresponding to a gain of \(g = 5 \times 10^4\). For the second and third stages, the signal beam size is magnified by a 1:4 telescope. In the second OPCPA stage, a 4 mm long BBO crystal is pumped with 5.45 mJ using a beam diameter of \(11 \times 7.9\) mm\(^2\) (at 1/e\(^2\) intensity) with an intensity of 16.3 GW cm\(^{-2}\). The signal is amplified by a gain of \(g = 20\) to a pulse energy of 0.5 mJ. The pump pulse is reflected back to achieve a further gain of \(2\) in a third OPCPA stage with a 2.2 mm BBO crystal, where the delay between pump and signal pulses can be adjusted. A total pulse energy of 1.12 mJ was achieved at 800 nm, corresponding to a final pump-to-signal conversion efficiency of 19.5\% (515–800 nm). The \(M^2\) was measured by fitting the caustic with \(M_x^2 = 1.1\) and \(M_y^2 = 1.2\). These \(M^2\) values are in good agreement with theoretical predictions [31].

As discussed in the introduction, FLASH has a burst for 800 \(\mu\)s at 10 Hz. To create a flat burst of OPCPA-pump pulses, the booster amplifiers need some time during the burst to stabilize in both pointing direction and energy. Therefore, the OPCPA-pump pulses have a burst longer than 800 \(\mu\)s (\(\text{figure 4(a), inset})\). The overlap of the laser pulses with the electron bunch is chosen over the flat part of the laser burst. From a known burst...
structure, the pulse energy can be measured. At different center frequencies, the pulse energy and selected pulse durations are shown in figure 4(a). Except for changing the dispersion management (section 2.2), no further optimization was carried out to maximize the conversion efficiency at each center frequency. Examples of near- and far-field beam profiles are given in figures 4(b) and (c), respectively.

Long-term energy, center frequency and pointing stability are very important for reliable FEL seeding operation. Figure 5(a) shows the OPCPA pulse energy of 1.12 mJ at approximately 800 nm with a long term fluctuation of 3.0% rms, and the OPCPA-pump energy of 5.41 mJ at 515 nm with 1.0% rms, measured for 23 hours based on the burst energy measurements. Figure 5(b) gives an example center frequency stability of 789.9 nm with 0.35% rms. Pointing fluctuations were measured for over 6 hours with values of 20.5 μrad rms and 17.0 μrad rms for x and y directions respectively, displayed as a histogram in figure 5(b), (inset). Except for the COG feedback, to regulate the center frequency, this system required no further need of feedback regulation for these measurements.

3. Power scaling limits

The above results demonstrate the feasibility of 112 W femtosecond OPCPA in burst mode with a duty cycle of $8 \times 10^{-3}$, where no heating effects were observed. Recent measurements of absorption coefficients of BBO and LBO [13] and calculations [31] have demonstrated the feasibility of much higher powers up to 1 kW in continuous mode. Therefore, presently, the limits placed on high power OPCPA are determined by the power output of the OPCPA-pump. For example, single rod fiber technology is restricted in power, and in particular, in single pulse energy. However, this problem could be overcome with coherent combining [32]. Presently, Innoslab technology, as used in this work, is capable of high powers, but the single pulse energy is limited to tens of millijoules. For a flexible high repetition rate FEL seeding application, higher pulse energies at high powers

Figure 4. (a) The dependence of pulse energy (left, black) and at selected frequencies pulse duration (right, red) on center wavelength for the three-stage OPCPA system. The lines are only used to guide the eye. Inset: typical 100 kHz burst structure of the OPCPA. The grey bar represents the area over which FEL seeding takes place. (b) Near- and (c) far-field beam profiles at 800 nm.

Figure 5. (a) Long-term stability of the pulse energy at approximately 800 nm (left, black) and pulse pump-energy at 515 nm (right, red) measured for 23 hours. (b) Long-term stability of the center frequency measured for 23 hours, and (inset) the pointing stability displayed as a histogram.
would be desired. We have therefore explored the possibility of using a thin-disk multipass amplifier in the burst mode of 800 μs at 10 Hz [17, 18].

For our application we extended the commercially purchased 1.5 kW AMPHOS Innoslab booster (figure 1) with a two-stage cascaded thin-disk amplifier system in a multipass configuration. Details of each individual multipass are found in [17]. The first stage of the thin-disk amplifier system is seeded with a spatially filtered 1 kW output of the Yb:YAG Innoslab amplifiers. The multipass is conceived for a total of 7 passes on a disk with a thickness of 750 μm, amplifying the seed to a total intra-burst output power of 6.74 kW, yielding a single pulse energy of 67.4 mJ at an intra-burst repetition rate of 100 kHz. To demonstrate the suitability of this amplifier system as a pump amplifier for OPCPA, the pulses have been compressed in a Treacy compressor. Figure 6 shows the spectrum (a) and the autocorrelation (b) trace of the amplified pulses. The spectral bandwidth of the amplified pulses is 1.7 nm (FWHM), centered at 1030 nm, yielding a Fourier transform limited (FTL) pulse duration of 930 fs. The autocorrelation shows that it was possible to compress the pulses to 970 fs, which deviates only 5% from the FTL. This demonstrates that sub-ps pulse durations are within reach with a multi-kW amplifier system.

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A further increase of the output power was demonstrated using a second thin-disk amplifier stage with again 7 passes on a disk with a thickness of 360 μm. With this second stage, it was possible to increase the output power of the entire amplifier system to a total of 13.7 kW in the burst, yielding a pulse energy of 137 mJ at 100 kHz.
repetition rate (figure 7(b)). For this case, the beam profile of the second amplifier stage was similar to the first stage thin-disk amplifier. This shows that output powers in the tens of kW range are feasible for OPCPA pump amplifiers using the thin-disk amplifier technology.

4. Secondary sources for seeding FELs

To make full use of the tunable OPCPA laser, broadband secondary sources, with center frequencies in the range between 200 nm and 300 nm, and corresponding beam lines, need to be developed. For the purposes of this paper, we have tested two different setups of THG and a FHG only at the fundamental frequency of 800 nm (figure 8).

In the first setup (figure 8(a)), the overlap between the fundamental and the second harmonic (SH) is achieved with a delay stage, and in the second setup (figure 8(b)), a calcite plate retards the fundamental pulse to the SH. Both THG-sets achieved the same conversion efficiency of 2.35% at 800 nm, yielding a spectrum supporting a Fourier-limited pulse of 32.7 fs (figure 9(a)). The conversion efficiency was measured with a fundamental pulse energy of 852 μJ at 800 nm, which generates a SH pulse energy of 200 μJ and a third harmonic (TH) pulse energy of 20 μJ with an in-burst fluctuation of 4.2% rms. For the following HGHG simulations (section 5), seeding will be examined at three frequencies—720 nm, 800 nm, and 900 nm—each with a pulse length of 30 fs. Conversion efficiencies, estimated using a fourth-order Runge-Kutta split-step Fourier algorithm [31], were found to be 5.8%, 9.3%, and 10.7% for 720, 800, and 900 nm, respectively. Scaling these values to the experimental value measured at 800 nm and using the results from figure 4(a), the expected energies for the TH are given in table 1. Additionally, the calculated conversion efficiency at 800 nm is about 4 times larger than the measured value. These experimentally measured conversion efficiencies and theoretical predictions were found to be similar to [33].

The fourth harmonic is generated by mixing the fundamental and the TH in a third BBO crystal (figure 8(c)). A time delay is introduced by splitting both beams and the polarization of the fundamental is

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**Figure 8.** The schematics (a) and (b) show two THG-sets with different time-delay configurations between the fundamental and SH. Setup (c) uses the fundamental and the TH generated in one of the THG-sets to generate the fourth harmonic. DS, delay stage. BS, beam splitter. BPF, band pass filter.

**Figure 9.** (a) THG-spectrum at a central wavelength of 266.2 nm with a bandwidth of 3.2 nm (FWHM). (b) The FHG-spectrum at a center wavelength of 199.1 nm and a bandwidth of 1.9 nm (FWHM).
changed with a waveplate. The measured spectrum is shown in figure 9(b), supporting a Fourier-limited pulse of 31 fs. The FHG efficiency from 800 nm to 200 nm is estimated to 0.098% (table 1).

For future development of broadband THG-setups, split and delay designs, similar to figure 8(a), are more flexible, and in addition, appropriate for ultrashort pulses. Broadband half-wave plates at 800 nm are commercially available. In figure 8(b), the combined $\lambda$ (400 nm)/$\lambda/2$ (800 nm) optics are only commercially available for a narrow bandwidth. Additionally for broadband applications, a careful choice of mirrors centered around 267 nm must be made, covering good dispersive and reflection characteristics over the bandwidth range of 240–300 nm.

5. HGHG simulations with THG injection for FLASH2

The FLASH user facility at DESY has been upgraded with a second undulator beamline FLASH2, and first SASE lasing of this new beamline has been recently reported [4, 34]. In the FLASH2 beamline, space has been reserved upstream of the SASE undulators for seeding hardware, and simulations for a FLASH2 HGHG option have been carried out [35]. As discussed in the Introduction, seeding improves the longitudinal coherence and shot-to-shot stability compared to the SASE process.

A possible HGHG setup at FLASH2 is shown in figure 10 and is composed of 3 parts, a modulator, a buncher and a radiator. The modulator is an undulator, which modulates the electron energy by the interaction between the electron bunch and the seed laser (figure 11(a)). The buncher is a magnetic chicane, which transforms this energy modulation into an electron density modulation (micro-bunching at the seed wavelength, figure 11(b)). Finally, the radiator produces coherent radiation at a wavelength of $\lambda$, from the periodic micro-bunched electron density. For more details about the HGHG process, see [36].
The HGHG process is simulated with the three dimensional code SIMPLEX (version 2.0.2) [37]. The main parameters used in the simulations are given in table 2. The seed laser is assumed to be Fourier-limited with pulse duration of 30 fs and an $M^2$-value of 1 for all simulated wavelengths. Although $M^2$-values greater than 1 can reduce the power contrast between the seeded and the unseeded FEL radiation, modal analysis, in the case of HHG seeding, suggests that the reduction is minor for $M^2$-values below 2 [38]. Similar studies are ongoing for HGHG, but are outside of the scope of this paper. Electron beam and undulator parameters are given by FLASH2 parameters. Because the K-parameter of the FLASH2 undulator has a maximum value of 2 rms, the maximum wavelength at a beam energy of 700 MeV is 42 nm. In the following section, simulations are performed covering seed wavelengths 240 – 300 nm, generated by using the THG of the tunable OPCPA (section 4). Therefore to reach wavelengths below 40 nm, the radiator was tuned to the 7th and 9th HGHG. Still higher harmonics were not chosen, because sufficient FEL power is not generated.

### 5.1. HGHG simulation results

The results of two selected simulations are given in figures 12 and 13: displayed is the HGHG peak power and peak photon flux in dependence on the seed energy (a); and temporal (b) and spectral (c) profiles taken at the optimal seed energy. In each case, the typical random ‘noise-like’ SASE temporal and spectral pulse profiles have been suppressed, and the output profiles are close to single mode. The temporal profiles are also Gaussian-like with pulse durations of 23.2 fs and 19.0 fs (FWHM), close to the Fourier limit, corresponding to figures 12(b) and 13(b), respectively. The spectral profile of the 7th HGHG using the THG of 800 nm (figure 12(c)) is Gaussian. But for the 9th HGHG using the THG of 720 nm (figure 13(c)), a small spectral distortion is evident, because the coherent seeding power starts to compete with the shot noise from the radiator.

At other frequencies, a summary of output parameters is given in table 3 and the peak power and peak photon flux against FEL wavelength are given in figure 14. Note: the 9th HGHG using the THG (figure 14) and the 7th HGHG using the FHG of the OPCPA fundamental have a similar wavelength range and both yield similar FEL peak powers and peak photon fluxes (results for the 7th HGHG using the FHG are not shown). However, the required simulated seeding laser energy exceeds the available FHG seed energy given in table 1.

Finally, simulations were performed in order to determine the influence of seeding laser energy fluctuations on the final FEL shot-to-shot energy fluctuations. Assuming the seeding laser has a energy fluctuation of 4.2%...
rms at 267 nm (section 4), the output fluctuations of the 7th and 9th HGHG would be 0.27% rms (see figure 12(a)) and 0.64% rms (results not shown) at around the optimal seed energy, respectively. Additionally, the effects of pointing fluctuations of the OPCPA (see section 2.3) have been simulated: a pointing error of 20 μrad changes the final FEL output energy by 0.26%.

6. Discussion and conclusion

This OPCPA system is designed for a user facility and demonstrates excellent long-term energy, center frequency and pointing stability. Except for the COG feedback on the center frequency, no further feedback regulation was required for these results. Improvements in short-term energy and pointing stability of the laser can be implemented by using a longer burst (see inset in figure 4(a)), allowing the Innoslab amplifier more time to reach equilibrium, as well as, by enclosing the laser in a sealed, temperature stable environment. This is especially important for the stretcher. Additionally, short-term stability is limited by bandwidth of the COG feedback system, which is restricted by the integration time and read out of a spectrometer. Cross correlation

Table 3. HGHG simulation results. HN (seed)—harmonic number of the fundamental OPCPA wavelength. HN (modulator)—harmonic number output of the HGHG. Seed energy—seeding laser energy at optimal seeding.

| OPCPA (nm) | 720 | 800 | 900 | 720 | 800 | 900 |
|-----------|-----|-----|-----|-----|-----|-----|
| HN (seed) | 3   |     |     |     |     |     |
| HN (modulator) | 9 | 7 |     |     |     |     |
| HGHG (nm)  | 26.7| 29.6| 33.3| 34.3| 38.1| 42.9|
| Seed energy (μJ) | 3.19| 3.67| 4.47| 3.19| 3.67| 4.47|
| Radiator segments | 6 | 5 | 5 | 4 | 4 | 3 |
| Peak power (GW) | 0.84| 0.78| 1.79| 0.81| 1.56| 0.76|
| Peak photon fluxa | 1.08| 1.04| 2.61| 1.18| 2.58| 1.19|

* In units of 10^12 photons/pulse/0.1% bandwidth.

Figure 13. Simulation of the 9th HGHG using the THG of the OPCPA at 720 nm and six radiator segments with K = 1.48 rms. (a) The dependence of HGHG output power (left) and photon flux (right, in units of number of photons at 0.1% bandwidth) on laser seed energy. HGHG output (b) temporal and (c) spectral profile at optimal seed energy of 3.19 μJ.

Figure 14. A summary of all simulations of the 7th and 9th HGHG using the THG of the OPCPA at 720, 800 and 900 nm. The dependence of peak power (left) and peak photon flux (right, in units of photons/pulse/0.1% bandwidth) on wavelength.
methods with a position sensitive detector have recently demonstrated a bandwidth of up to 1 kHz [39], but with increased setup complexity. However, short-term fluctuations of the seed laser have only a minor influence on the shot-to-shot FEL energy (section 5). In practice, the FEL fluctuations will be dominated by other factors, such as, fluctuations in bunch charge or arrival time of the electron bunch. In the case of maintenance-free operation of days and weeks, the Ti:sapphire oscillator frontend could be replaced by a supercontinuum generated signal, based on stable fiber oscillator and amplifiers, as we demonstrated in [11]. In addition, depending on the long-term stability (temperature and humidity) of the laser laboratory, further feedback systems could be carried out on the booster amplifiers.

To increase the burst power of this OPCPA, we demonstrated for the first time a one-stage multipass thin-disk amplifier with a pulse energy of 67.4 mJ compressed to 970 fs (FWHM) at a burst pulse rate of 100 kHz. Additionally, a second multipass thin-disk amplifier was used in cascade for further amplification up to 137 mJ at 100 kHz, resulting in a final output power of 13.7 kW in burst mode. The pulses of the additional stage were, however, not yet compressed. Further improvements (e.g. sealed environment, length stabilization of the multipass) in the experimental setup will lead to an even more stable pump pulse source for the OPCPA. However, this development demonstrates the scaling prospects towards kW-output power femtosecond OPCPA with energies exceeding 10 mJ at 100 kHz [13].

A preliminary simulation of a HGHG setup at FLASH2 was carried out. Based on the experimentally measured THG conversion factor at 800 nm, as well as using the OPCPA results from figure 4 and scaling to other wavelengths using simulations, table 1 was provided, giving the expected pulse energies at other wavelengths. From table 1, the seed laser energies at 100 kHz exceed the required HGHG energies (from the 7th and 9th HGHG using the THG of the OPCPA, see table 2) by factors 3.4, 7.2 and 5.9, for OPCPA wavelengths of 720 nm, 800 nm, and 900 nm, respectively. Experience shows that a minimum of a factor of 2 to 3 of the total energy is lost because of transport and uncertainties with the overlap between the electron beam and the seeding laser. Thus, with this tunable OPCPA, it is possible to seed FEL wavelengths covering almost the complete range from 26.7 to 42.9 nm. More detailed simulations, which also include modal analysis of the HGHG seeding laser, variation of the modulator length, and schemes to lower the FEL wavelength down to 4 nm (for example, a cascaded HGHG scheme [40]) are beyond the scope of the present work and will be published elsewhere.

In conclusion, a 112 W burst mode OPCPA has been developed with good beam quality and reliable long term stability needed to seed high repetition rate FELs. The presented pump developments (section 3) promise to increase the OPCPA burst power by a factor of 10. Additionally, HGHG simulations were carried out using the package SIMPLEX covering a wavelength range from 26.7 to 42.9 nm. The expected FEL pulses are close to single mode near the Fourier limit. Sufficient seed laser energy from the OPCPA is expected to cover these wavelengths using a THG source at 100 kHz. With the expected developments of the thin-disk amplifier, seeding would be possible at even higher repetition rates.

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