HIGH REPETITION RATE SEEDING OF A FREE-ELECTRON LASER AT DESY HAMBURG*

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Abstract

The performance of fourth generation light sources is of interest in many fields in natural science. Different seeding schemes for FELs are under investigation to improve timing stability, pulse shape and spectrum of the produced XUV or X-ray pulses. One promising scheme is direct seeding by high-harmonic generation (HHG) in gas. A seeded free electron laser with a tunable wavelength range from 10 to 40 nm and a bunch frequency of up to 100 kHz (1 MHz upgraded), as proposed for FLASH II (collaboration HZB/DESY), is difficult concerning conversion efficiency and stability of an HHG source. Here, the most challenging task is the conception of a laser system with a repetition rate of 100 kHz (1 MHz upgraded) in burst mode. The key parameters for this laser amplifier system are pulse energies of 1-2 mJ and sub-10 fs pulse duration. We report on the development status of the required laser system for the seed source and give an overview of first concepts for the HHG target setup which can comply with the requirements of a new seeded FEL at DESY.

INTRODUCTION

Free-Electron-Lasers (FELs) like the **F**ree-Electron-**Las**er in **H**amburg (FLASH) at DESY deliver intense coherent radiation within a wavelength range down to soft x-rays. FLASH consists of 7 superconducting acceleration modules accelerating the electron bunches to an energy of max 1.2 GeV and a third-harmonic cavity leading to a quasi-gaussian longitudinal electron beam profile [1]. The radiation is produced in a 30 m long undulator section with fixed gap and permanent magnets. The FEL currently relies on the SASE process (Self-Amplified-Spontaneous-Emission), thus the amplification starts up from noise which leads to shot-to-shot fluctuations of about 18% (rms) due to the reduced longitudinal coherence [2]. The second effect is a large arrival time jitter at the experimental station mainly due to the unkwown timing of the electron bunches. This reduces the temporal resolution for pump-probe experiments to ≈ 100 fs (rms). The jitter limits the applicability for precise pump probe experiments.

One promising method to improve both the longitudinal coherence and the timing performance of the FEL is direct seeding via High-Harmonic-Generation (HHG) from an infrared laser in noble gases [3]. In that case, the FEL process does not start from noise but from a defined external seed source which imprints its characteristics on the FEL pulse. This also leads to an improved shot-to-shot intensity stability. The feasability of a seeded FEL using the accelarator of FLASH will be studied at the experiment sFLASH [4]. To incorporate new developments for FELs in the DESY facility collection, a new FEL, FLASH II (collaboration HZB/DESY), is planed using the same linear accelerator (linac) as FLASH but having its own undulator section and experimental hall [5]. This FEL will be a user facility with SASE operation mode, but also with direct HHG seeding, seeding via cascaded High-Gain-Harmonic-Generation (HGHG) [6] and seeding in a hybrid HHG seeded HGHG mode.

THE NEW FACILITY FLASH II

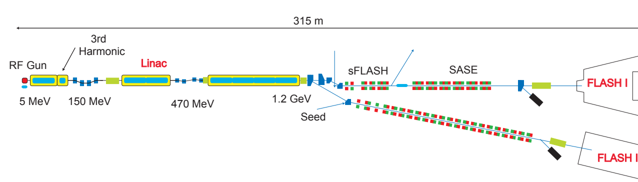

Figure 1: Layout of FLASH II. The new FEL user facility shares the same linac as FLASH and provides wavelengths from 4-60 nm in SASE mode or 4-40 nm in three differnt seeding modes.

A schematic of FLASH II is shown in figure 1. FLASH II shares the same acceleration structure as FLASH (will be named FLASH I in the following) which makes this new FEL cost effective. In addition, FLASH II is separated from FLASH I in a way such that this facility can be maintained during FLASH I operation. In contrast to FLASH I, the new facility will have variable gap undulators so that despite a possible electron energy change in the linac the SASE wavelength range of 4-60 nm stays flexible. Both the physical seperation and the variable gap make FLASH II operation more independent of FLASH I which makes the FLASH facility user friendly. The new FEL will be operated with max 800 pulses at a 1 MHz bunch repetition

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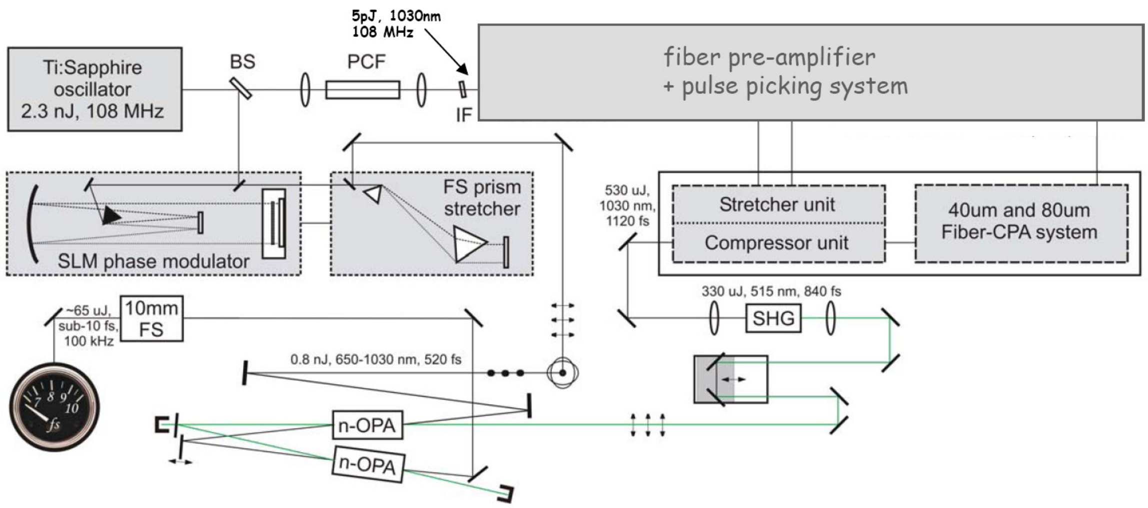

Figure 2: Schematic experimental setup of the OPCPA system including Ti:Sapphire oscillator, fiber preamplifiers, high power fiber CPA system, pulse shaper, prism stretcher, two stage optical parametric amplifier and fused silica bulk compressor. (SHG - second harmonic generation, OPA- optical parametric amplifier, PCF - photonic crystal fiber, FS - fused silica, BS - beam splitter, IF-interference filter, SLM - spatial light modulator)

rate at intervals of 0.1 sec. The seed pulse will be coupled into the FEL at a position appr. 10 m from the undulator entrance. This ensures that the seed will be moderately focused into the FEL undulators having an adequate overlap within one or two gain lengths being approximately 1-0.5 m for 10-40 nm respectivly. In addition, it will be possible to combine HGHG seeding with the direct seed pulse which opens the possibility to reach the water window with the outcoming FEL radiation.

More information about layout, design concept and status of FLASH II can be found in [5].

THE LASER SYSTEM

In SASE mode the repetition rate and pulse characteristics of the FEL output are purely defined by the electron bunches. Seeded FEL pulses are intrinsicly predefined by the seed source properties which, in case of HHG, are driven by a laser system. Thus, the development of an appropriate laser amplifier is a key challenge of the seeding source. At FLASH II the aim is to seed at least 10% of the max possible bunches in a wavelength range from 10-40 nm which requires a repetition rate of 100 kHz with 10 Hz bursts (burst duration is 800 μs). The laser has to be sychronized with the RF-Frequency of the FLASH linac system. Additionally, it is necessary to produce sufficient energy in a single harmonic of the HHG spectrum to overcome the SASE level which acts as noise in a seeded FEL. First estimations lead to a shot noise level in the range of kilowatts, thus the pulse energy of the laser system has to be 1-2 mJ to reach nanojoule energy level within a single harmonic considering present conversion efficiencies. To enable short FEL pulses and high efficiencies in the HHG process, the aim is to get sub-10 fs pulse duration for the seed pulses.

A specially designed amplifier system with a fiber-pumped OPCPA system as front end developed at DESY together with the IAP Jena will cover these requirements. The OPCPA concept combining the chirped pulse amplification technique with the optical parametric amplification process is well suited for ultra-short pulse amplification up to highest pulse energies and average powers [7].

As a possible seed source, the OPCPA system has to be pumped by a very high average pump power laser. Fiber laser systems which reached recently the millijoule pulse energy range with femtosecond pulse durations and repetition rates above 100 kHz [8] are ideally suited as front-end for the OPCPA pump amplifier. A schematic of the current design status of the OPCPA system is shown in figure 2. A Ti:Sa Oscillator with a central wavelength of 760 nm seeds the fiber pump amplifier and the first OPA crystal (BBO Type I) at the same time. In a stretcher/compressor scheme the seed and pump pulse durations get adapted to each other to match the gain window of the pump pulses with a gain of $> 10^4$. First tests were made with 60 kHz repetition rate which led to 35 μJ pulse energy and 7.8 fs pulse duration [9]. The energy stability was as good as 1.3% rms and the calculated peak power amounted to 3.4 GW. Recently, a second experiment was performed with the current setup of the OPCPA system (figure 2) [10]. Compared to the earlier test, the system was upgraded with one further OPA stage and the repetition rate was increased to 96 kHz. An average power of 6.7 W reached with the current configuration leads with pulse durations of 8 fs and pulse energies of 70 μJ to a pulse peak power higher than 6 GW. This is the best performance reported for any fiber driven laser system. The next steps include efforts to increase the pulse energy of the system. This will be achieved by increasing the pump energy of the OPA system by implementing a further amplication stage behind the fiber pump amplifier. Including this stage, the pump energy is aimed to be 20 mJ in the fundamental corresponding to appr. 10 mJ in the 2nd

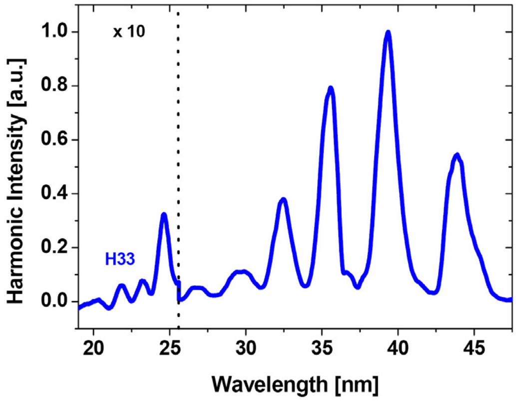

Figure 3: Measured harmonic spectrum in Krypton. The cut-off region is magnified by a factor of ten.

harmonic at 515 nm. Furthermore, the burst mode has to be implemented to match the repetition rate of FLASH II. Finally, a Carrier-Envelop-Phase (CEP) stabilized system is desireable for pump-probe and seeding applications (see below). So far, this task has not really been solved yet. However, CEP stabilization has been shown for a short time with our system [10].

THE HHG SOURCE

For FEL seeding HHG in noble gases has proven to be an adequate tool [11, 12, 13, 3]. The challenge of seeding FLASH II is the tunability of wavelength from 10-40 nm and the stability over at least one user shift of 7 hours at repetition rates of 100 kHz. Additionally, the seed power has to exceed the shot noise level at least by two orders of magnitude to get an adequate signal-to-noise contrast. These are no trivial demands on a seed source. However, the stability issue has to be solved with a stable laser system and is thus a task important for the development of the OPCPA amplifier. The tunability of a HHG Source requires flexibility of gas choice and pressure control. In general HHG produces a distinct spectrum with harmonics appearing at odd multiples of the fundamental. A tunable source would imply to overcome this structure ending up in a continuous or quasi-continuous spectrum such that the FEL can amplify any wavelength within the resonance condition. This could be solved with stabilized CEP of the few-cycle laser which would lead to a continuous HHG spectrum [14]. However, even with no phase stabilization the spectrum becomes quasi-continuous in the cut-off region with sub-10fs pulses. In addition, applying ω-2ω mixing would also break the symmetry of the process and leads to even harmonics in the HHG-spectrum [15].

Collective effects caused by the dispersion of free electrons, the neutral gas and other effects will affect the efficiency of the total HHG process. To increase the efficiency, quasi-phasematching schemes have to be applied for our seeding source [16]. A first experiment with HHG was performed recently with the current OPCPA setup described above [10]. The measurement was done with the laser beam of 8 fs pulse duration and 53 μJ energy focused down to $(61 \times 91)\,\mu$m in a Krypton gas jet which corresponds to an estimated intensity of $2.9{\cdot}10^{14}$ W/cm^2. Figure 3 shows the resulting spectrum going down to a wavelength of 22.1 nm corresponding to the 33th harmonic of the laser light. The wash-out effect in the cut-off region is due to the short pulse duration containing only a few cycles. The cut-off has to be extended to shorter wavelength for the seeding application by using different gases and HHG schemes.

CONCLUSION

We introduced the project of a new seeded FEL at DESY Hamburg. It will be seeded with a burst mode repetition rate of 100 kHz in a wavelength range of 10-40 nm exhibit a challenge to the laser amplifier development. A new OPCPA system is under develeopment and first tests showed impressive performance of the fiber pumped system at 96 kHz. Further research has to be done to increase the energy yield and to implement the burst mode required by the FEL.

Higher harmonics will be produced via HHG in gases and a first experiment showed good feasibility with the current OPCPA setup. Further effort has to be invested to improve the efficiency of the HHG process and to extend the spectrum to shorter wavelengths. CEP stabilization would be desireable for the tunability of the seeded FEL.

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