RESULTS AND PERSPECTIVES ON THE FEL SEEDING ACTIVITIES AT FLASH*

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ABSTRACT

In recent years, several methods of free-electron laser (FEL) seeding, such as high-gain harmonic generation (HGHG), self-seeding, or direct FEL amplification of external seed pulses, have proved to generate intense, highly coherent radiation pulses in the extreme ultraviolet (XUV), soft- (SXR) and hard (HXR) X-ray spectral range. At DESY in Hamburg, the FEL facility FLASH [1] is currently being upgraded by a second undulator beamline (FLASH2, [2]) which allows for the implementation of various seeding schemes. The development of high repetition-rate, high-power laser systems allows for the production of seed sources which match the bunch-train pattern of FLASH. Furthermore, the FLASH1 beamline arrangement is well suited for testing various seeding schemes including HGHG, EEHG, HHG-seeding, and hybrid schemes. In this contribution, we give an overview of latest results and planned FEL seeding activities at FLASH.

INTRODUCTION

The initiation of the FEL process by means of external laser seeding allows to generate fully coherent FEL radiation that is intrinsically synchronized for pump-probe experiments. In recent years, several methods for external laser seeding have been studied, such as high-gain harmonic generation (HGHG), direct FEL amplification, or echo-enables harmonic generation (EEHG) as well as hybrid or cascaded schemes. Among them, the HGHG FEL seeded at the third harmonic of a Ti:sapphire laser has proved to work reliably down to the extreme ultraviolet (EUV) spectral range as shown by the successful operation of the seeded FEL facility FERMI@Elettra [3]. Direct amplification of higher-harmonics from Ti:sapphire laser pulses up to the 21st harmonic has been demonstrated at FLASH in combination with high peak-current electron bunches [4].

The FEL user facility FLASH at DESY has been upgraded recently by a second undulator beamline [5]. This new beamline is going to be commissioned in 2014 for SASE operation. In addition to that, an injection beamline for seed radiation as well as a modulator and a chicane are planned for installation end of 2014. The seed radiation is generated from a high-repetition rate optical parametric chirped pulse amplifier (OPCPA) system currently under development at DESY [6]. It will allow to seed the FEL in the multi-bunch burst mode. Beside the planned seeded FEL user facility at FLASH2, a program for further R&D of seeded FELs is planned at FLASH1 conducted by a collaboration of DESY, Hamburg University, and TU Dortmund University. These activities will first of all provide operational experience for a UV seeded HGHG setup and its performance under variation of different machine parameters. Furthermore, the experimental layout at the FLASH1 beamline offers promising possilities to study EEHG with harmonics down to the EUV.

EXPERIMENTAL LAYOUT

Figure 1 shows the schematic layout of the FLASH facility. A fast kicker-system after the superconducting linac distributes electron bunches into both undulator beamlines, which are shown in more detail in Fig. 2(a) and Fig.2(b).

FLASH1

The FLASH1 beamline is equipped with four different types of undulator systems. The first section contains two 1-m long electromagnetic undulators (ORS1 and ORS2) with an undulator period of 20 cm originally installed for electron diagnostics purposes [7]. Each of these undulators is followed by a magnetic chicane (C1 and C2). ORS1 has a vertical deflection plane, while ORS2 deflects horizontally. The maximum K-value (peak) is 10.8 for both devices. The second undulator system contains a variable-gap undulator with a period of 31.4 mm, an effective length of 10 m, and a maximum K-value of 2.7. It was installed 2009 for direct seeding experiments and covers a wide wavelength range in the EUV. A subsequent magnetic chicane allows to insert a set of mirrors extracting the FEL radiation to dedicated diagnostics. The electron beam further travels through a 10 m long diagnostic and matching section into the fixed-gap undulator system. This 27 m long undulator has a fixed K-value of 1.23 and a period of 27.3 mm. The last undulator is a 4 m long electromagnetic insertion device to generate radiation in the THz spectral range for pump-probe applications.

FLASH2

The new FLASH2 beamline will be equipped with 2.5 m long insertion devices with a period of 31.4 mm and a maximum K-value of 2.7. Behind the radiation shielding wall, twelve of these undulators modules will be installed as indicated in Fig. 2(b). This total active undulator length of

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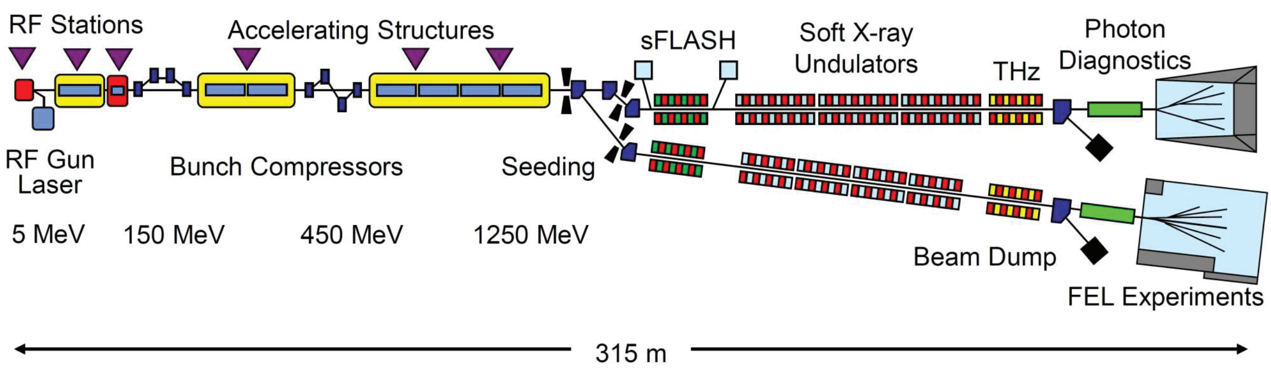

Figure 1: Schematic layout of the FLASH facility.

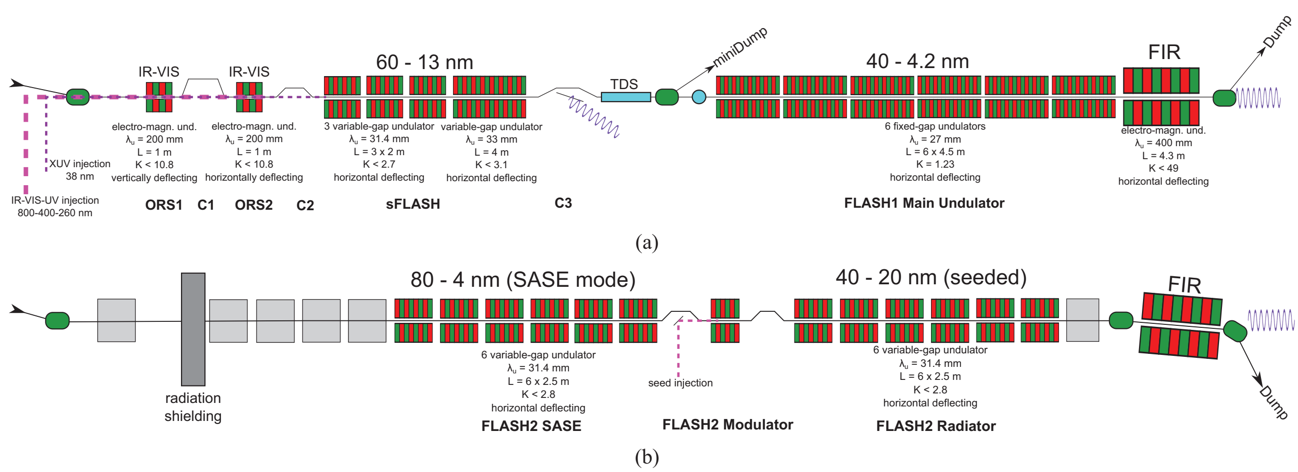

Figure 2: Schematic layout of the FLASH1 (a) and FLASH2 (b) undulator beamlines. The beam direction is left to right. Information on the different undulator systems are indicated as well as the possible wavelength range for the first harmonic.

12x2.5 m is needed to reach SASE saturation at 4 nm with the FLASH beam parameters. First simulations show that for the HGHG seeding, only six undulator modules are needed. Therefore, in the middle of the undulator section there are three cells which contain the UV injection setup, a modulator, and a bunching chicane. The last six undulator modules act as the HGHG radiator or as additional SASE undulators.

SUCCESSFUL DEMONSTRATION OF 38NM SEEDING

Direct HHG seeding at the 21-st harmonic of an $800\,\mathrm{nm}$, $15\,\mathrm{fs}$ (rms) laser (seed radiation wavelength $\lambda = 38\,\mathrm{nm}$) was successfully demonstrated at FLASH in April 2012 [4, 8].

After establishing the six-dimensional overlap in the dimensions $\{x, x', y, y', t, \lambda\}$ we observed an energy contrast of up to five compared to average SASE energy. To study the impact of temporal offsets, we performed time scans in $0.1\,\mathrm{ps}$ steps around the overlap position. Such a measurement is shown in Fig. 3. For every scan step, we acquired 100 data samples with the HHG source on and 100 with HHG source off and computed the correlation of the HHG seed energy and of the FEL pulse energy after the sFLASH undulators. An alternative analysis of the same data set is shown in Fig. 4. When the HHG source is off, the FEL produces only SASE radiation. The shot-to-shot distribution of the SASE pulse energies is described by the Gamma probability distribution [9]. In contrast, when the HHG source is on, the FEL pulse energy distribution will be different, ideally one would expect a normal distribution describing the fluctuations of the seed laser. However, in our case the arrival time jitter of the electron bunch has been measured to be $500\,\mathrm{fs}$ pk-pk. In addition to that the laser system has no active arrival time compensation. Therefore, the optimal temporal overlap is achieved only for a fraction of the bunches. Hence, the effect of the seeding (i.e. with HHG on) will show up as a peak in the higher energy range of the histogram.

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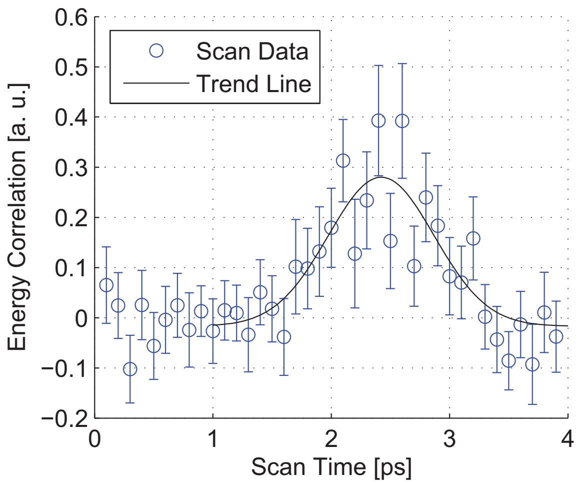
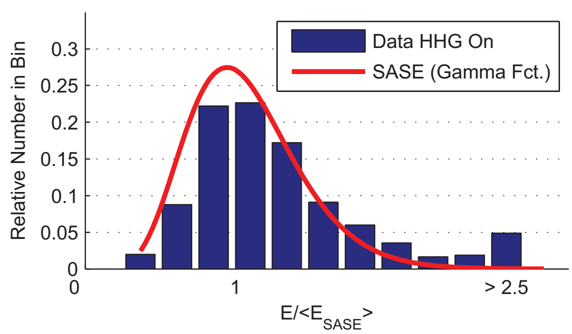
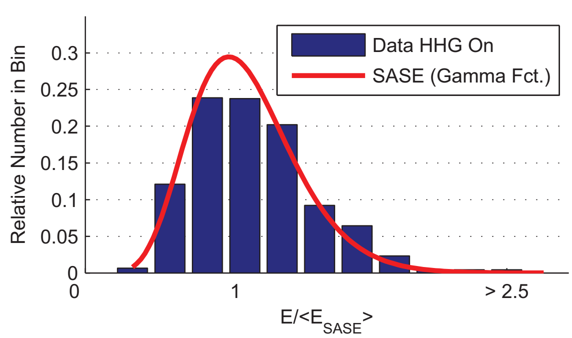


Figure 3: Correlation data of the XUV seed pulse energy and the output energy as obtained in the longitudinal scan. We computed the correlation values and the standard deviations ($\pm 1\sigma$ indicated by error bar) for every longitudinal scan step.



(a) Scan steps $t = 2.0$ ps, . . . , 2.8 ps of the longitudinal scan.



(b) Scan steps $t = 0.7$ ps, . . . , 1.5 ps of the longitudinal scan.

Figure 4: Impact of seeding on the pulse energy distribution. (a) Within the time range with overlap. (b) For comparison, the same procedure was applied to neighboring points starting at the distance 0.5 ps from the time range with overlap.

From the same dataset as discussed in Fig. 3, the time steps in the range $t = 2.0$ ps, . . . , 2.8 ps were merged into a dataset with 1800 data points total (900 with HHG on and 900 with HHG off). The result of this data analysis is shown in Fig. 4(a). The histogram represents the distribution of the FEL pulse energy E with the seed source on. The red curve indicates the probability distribution of the SASE pulses (HHG off, average pulse energy $\langle E_{\mathrm{SASE}} \rangle$). For this figure, the "HHG on" data was binned with the highest bin containing all samples with $E/\langle E_{\mathrm{SASE}} \rangle > 2.5$. For our data, about 5% of all pulses fall in this bin. As expected, the difference between HHG on and off cases is significant and visible as a peak in the high energy range of the histogram. Also from this analysis one can estimate the ratio of the seeded and unseeded pulses.

As a cross-check, the same analysis has been repeated for the scan steps $t = 0.7$ ps, . . . , 1.5 ps, i.e. for time delays where we do not expect any temporal overlap (compare Fig. 3). This time range has a distance of 0.5 ps to the time range processed above. As one can see in Fig. 4(b), no bin shows significant differences from the expected SASE distribution. This is in agreement with the expectation that no seeding takes place.

SEEDING PLANS FOR FLASH1

After the successful demonstration of direct HHG seeding at a wavelength of 38 nm, the FLASH seeding team prepares to investigate different seeding schemes including HGHG (single stage and cascaded seeding), EEHG and HHG. This section summarizes these activities.

HGHG Seeding at FLASH1

The first priority for the FLASH1 seeding program after the 2013 shutdown will be the commissioning of a UV seeded HGHG scheme in order to get operation experience with for FLASH2 and to study the performance of HGHG under various machine conditions. After injection into the electron beamline upstream of the last dipole of the FLASH1 energy collimator, the $\lambda = 267$ nm seed radiation will be brought into overlap with the electron bunches either in the first or the second ORS undulator (ORS1, ORS2 in Fig. 2(a). The energy modulated electron beam is then sent into a chicane at the exit of the modulator, turning the energy modulation into a density modulation. One or more of the subsequent sFLASH undulator modules are used as the radiator. The seeded FEL radiation is extracted in the following chicane (C3) into dedicated diagnostics.

EEHG Seeding at FLASH1

With two pairs of short electro-magnetic undulators and chicanes (ORS1 and C1, ORS2 and C2) already installed at the entrance of the sFLASH undulator system, the present hardware configuration at FLASH1 can be used to demonstrate EEHG seeding ([10] and the references therein). For this, 267 nm UV laser pulses will be injected into the electron beamline. As the polarizations of the two ORS undulators are orthogonal, the two laser pulses used to modulate

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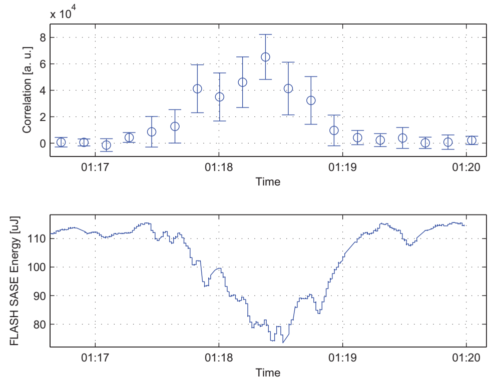

Figure 5: Scan of the relative timing of the electron bunches and the 800 nm laser pulses in 100 fs steps. Around the position of optimal temporal overlap (indicated by the maximum correlation, see text for details) the FLASH SASE pulse energy exhibits a significant decrease.

the electron beam in ORS1 and ORS2 have to be orthogonal, too. In [11] the use of a birefringent crystal was proposed to produce laser pulses with the required properties and also compensate for the delay introduced by the first chicane. As in the HGHG case, the sFLASH undulator system will act as radiator for the seeded light pulses.

Longitudinal Space Charge Amplifier (LSCA)

In January 2013 we observed a significant decrease of FLASH SASE energy in coincidence with laser-electron overlap of the 800 nm laser and the electron bunches in the first ORS undulator. This effect has not been observed in the sFLASH SASE pulse energies. We conclude that the well-defined density modulation imprinted by the laser in the undulator-chicane combination acts as 'seed' that is amplified by the LSCA (Longitudinal Space Charge Amplifier, [12]) process, which has received much attention recently [13]. As the electron bunch traverses the electron beamline, amplification of the density modulation can take place in combinations of focusing transport channels and chicanes. Finally, arriving at the FLASH Main Undulator, SASE production is suppressed.

Another consequence of the electron bunch density modulation created by the laser is the emission of coherent undulator radiation in the second ORS undulator. Although the additional photon pulse energy emitted by ORS2 could already be used as an indicator for precise temporal overlap at the sub-picosecond level, we additionally switch the laser on and off regularly in order to exclude artifacts introduced by slow drifts of the machine or the laser parameters. Finally we compute the correlation of the laser status (on or off) and the photon pulse energy, allowing us to obtain the position of optimal temporal overlap. Fig. 5 shows a scan of the temporal overlap in 100 fs steps, the decrease of the measured FLASH SASE pulse energy close to the region of optimal overlap is clearly visible.

Improvement of Direct HHG Seeding at FLASH1

Direct HHG seeding at $\lambda = 38\,\mathrm{nm}$ was demonstrated by the sFLASH experiment in April 2012 [4]. The data analysis presented above reveals that only a fraction of the electron bunches is being seeded. Reduction of the relative arrival time jitter of the electron bunches and the HHG seed pulses is expected to improve the situation. Therefore, we are preparing seeding runs in FLASH multi-bunch operation, taking advantage of the existing fast longitudinal feedback system pushing the arrival time jitter of the electron bunches down to $\sigma_t = 25\,\mathrm{fs}$ [14]. Together with an active arrival time drift compensation for the seed laser, we expect a significant improvement of the seeding rate for seeding with short bunches. The sFLASH photon diagnostics hardware in the extraction branch was already upgraded to support multipulse operation, now providing energy measurements for individual photon pulses for a 1 MHz bunch pattern. Additionally, time-resolved FEL diagnostics, such as THz streaking, will allow to observe the effect of seeding directly in the time domain. Once these items are implemented, the HHG seeding will be continued.

SEEDING PLANS FOR FLASH2

Several options for seeding the FLASH2 FEL have been discussed in the past [15–17]. The baseline design for FLASH2 foresees SASE operation and delivery of seeded FEL radiation below 40 nm. The UV seed is provided by frequency conversion of near-infrared (NIR) laser pulses generated in a high-repetition rate OPCPA system currently under development. The target parameters for the NIR laser are to generate around 1 mJ pulse energy within a pulse duration below 40 fs. In the first stage, the system operates in a 10 Hz burst mode with an intra-burst repetition rate of 100 kHz. Later, the intra-burst rate should be adapted to the 1 MHz of the accelerator. We expect to have all hardware for FLASH2 seeding installed by the end of 2014. Options for future upgrades reaching shorter wavelengths in seeded operation are under investigation, including EEHG as well as staged and hybrid schemes.

SUMMARY

With the successful demonstration of HHG seeding at 38 nm using 15 fs short laser pulses and highly compressed electron bunches (>1 kA), the sFLASH collaboration could set an important milestone in the improvement of seeded FEL technology. The present extension of the FLASH facility at DESY will pave the way for a high-repetition rate seeded FEL facility at FLASH2. In 2014, a dedicated HGHG program at FLASH1 is planned, including tests of further options like EEHG or hybrid schemes.

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