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STATUS OF THE SEEDING DEVELOPMENT AT sFLASH

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Abstract

sFLASH is the experimental free-electron laser (FEL) setup producing seeded radiation installed at FLASH. Since 2015 it has been operated in the high-gain harmonic generation (HGHG) mode. A detailed characterization of the laser-induced energy modulation, as well as the temporal characterization of the seeded FEL pulses is possible by using a transverse-deflecting structure and an electron spectrometer. In this contribution, we present the status of the sFLASH experiment, its related studies and possible developments for the future.

INTRODUCTION

Since 2005, the free-electron laser (FEL) facility in Hamburg, FLASH, at DESY has been operated as a user facility [1]. The wavelength range was upgraded in several steps to cover an interval from about 4.2 nm to 45 nm at the beamline FLASH1. Recently, a second undulator beamline, called FLASH2, was built and commissioned to serve simultaneously two user end stations [2]. Both the beamlines are operated in the self-amplified spontaneous emission (SASE) mode [3, 4].

As a SASE FEL starts up from the random shot noise in the electron beam, the FEL radiation has poor spectral stability and limited longitudinal coherence. Seeding the FEL with a fully coherent source such as a laser, offers an option to overcome these limitations as experimentally demonstrated in the FERMI FEL in Trieste, Italy [5].

At DESY, an experimental setup for seeding developments has been installed upstream of the FLASH1 main SASE undulator in 2010 [6]. After successful demonstration of direct-HHG seeding [7] at 38 nm in 2012 [8], the focus of the seeding R&D at FLASH has turned on HGHG [9] and echo-enabled harmonic generation (EEHG) [10] seeding [11, 12].

The results obtained at the sFLASH seeding experiment guide the design process of the proposed FLASH2 seeding option [13].

In this contribution, the performance of HGHG seeding at sFLASH is described and we present the current status of the FEL seeding developments at DESY.

EXPERIMENTAL SETUP

The sFLASH seeding experiment is installed at the FEL user facility FLASH [14]. Figure 1 shows the schematic layout of the sFLASH experiment.

The electron bunches arrive from the FLASH linear accelerator with a repetition rate of 10 Hz, a typical charge of 0.4 nC and an energy between 680 MeV and 700 MeV. At the exit of the energy collimator, the sFLASH section starts with two electromagnetic undulators (called modulators, labelled MOD1 and MOD2 in Fig. 1) with 5 full periods of period length $\lambda_u = 0.2$ m and orthogonal polarization [15], each followed by a magnetic chicane (labelled as C1 and C2). In the HGHG experiment, MOD1 and C1 are not used and the interaction of the seed laser pulse with the electron bunch takes place in MOD2. Here, the seed pulse generates a sinusoidal energy modulation in the electron bunch that afterwards is converted into a density modulation by chicane C2.

The Seed Laser

The 266 nm seed pulses are generated by third-harmonic generation (THG) of near-infrared (NIR) Ti:sapphire laser pulses. The maximum energy of these UV seed pulses at the entrance of the vacuum transport beamline to the modulator undulator is 500 µJ. At the interaction point with the electron beam, the Rayleigh length of the UV beam is between 1.5 and 3 m depending on the focus of the laser.

A single-shot cross-correlator for NIR and UV pulses in the laser laboratory enables to measure the UV pulse duration, that is typically between 250 and 280 fs FWHM. The NIR pulse duration is simultaneously measured with a single-shot auto-correlator and it is about 50 fs FWHM. The longitudinal position of the beam waist can be adjusted by changing the NIR focusing into the THG setup. Before and after MOD2, the seed beam position and size are measured using Ce:YAG fluorescence screens. In the configuration in which the beam waist coincides with the center of the modulator module, a characteristic value for the rms beamsize at the screen positions is $\sigma_r = 0.33$ mm.

Latest upgrades Until the end of 2016, the THG setup was installed in the FLASH tunnel, limiting maintenance access. Now, this setup is installed in the seed laser laboratory and can be accessed when needed which facilitates the optimization of the UV seed beam quality. In particular, thanks to the more generous spaces inside the laser laboratory, a second THG setup has been installed next to the existing one and the NIR laser transport system has been modified in order to obtain two properly focused pulses that enter each in one of the two triplers. The new UV beam is focused into MOD1 by a Galilean telescope that has been installed in the FLASH tunnel before MOD1 in July this year. The

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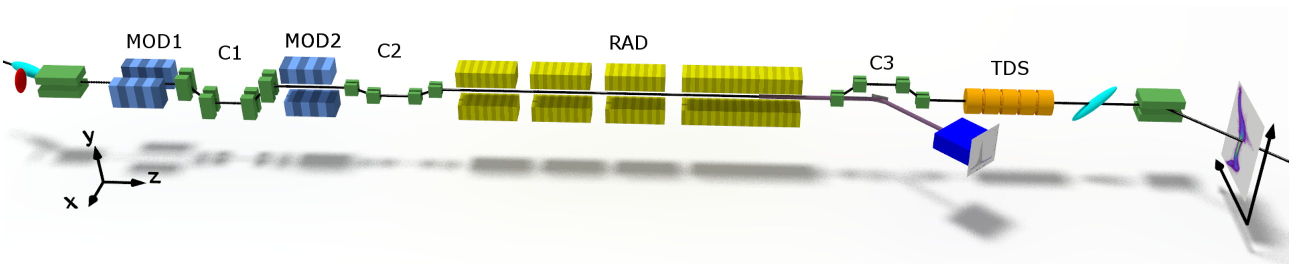

Figure 1: Layout of the sFLASH seeding experiment.

already existing UV seed source continues to be focused into MOD2 through a telescope in the laser laboratory. This setup enables experimental EEHG studies as presented in [16].

Radiator section

Four variable-gap undulators modules (labeled RAD in Fig. 1) with a total effective length of 10 m act as the FEL radiators. These undulators are tuned at an harmonic of the seed laser in order to make the current-modulated electron bunch initiate the FEL process. Downstream of the sFLASH radiator, the electron beam is guided around the radiation extraction mirrors by chicane C3 and it enters into the transverse-deflecting structure (TDS). The TDS is followed by a dispersive dipole spectrometer that deflects the electron bunch into a beam dump. An observation screen is installed in the dispersive section between the dipole spectrometer and the beam dump on which the longitudinal phase space distribution of the electron bunch can be observed. From these measurements, the parameters of the electron bunch such as current and slice emittance are obtained [17, 18]. When operated with uncompressed electron bunches (in order to exclude FEL gain), the uncorrelated energy spread of the electron bunch can be extracted by analysing coherent harmonic generation (CHG) emission at several harmonics [19]. The energy resolution of this technique significantly surpasses that of the TDS setup.

FEL Diagnostics

The seeded FEL pulses are transported to an in-tunnel photon diagnostics section, where different detectors are available: fluorescence screens for transverse beam diagnostics, a photon energy monitor based on a microchannel plate, and a high-resolution spectrometer for wavelengths from 4 to 40 nm [20].

Alternatively, the seeded FEL beam can be transported to a dedicated diagnostics hutch outside the radiation shielding of the accelerator. Here, the temporal profile of the FEL pulse can be studied utilizing a THz-streaking technique [21, 22]. A second, non-invasive method to obtain the power profile of the photon pulses is to extract this information from longitudinal phase space distributions of the electron bunch [17, 18, 23].

Table 1: Experimental Parameters for HGHG.

	Parameter	Value
Modulator	period length λ_u^{MOD}	0.2 m
	N_u^{MOD}	5
	K_{MOD}	2.77
Radiator	period length λ_u^{RAD}	31.4 mm
	N_u^{RAD}	318
	K_{RAD}	2.61
Chicanes	R_{56} C1	not used
	R_{56} C2	50-200 µm
	R_{56} C3	190 µm
Electron Beam	energy	680-700 MeV
	charge	0.4 nC
	bunch duration	>500 fs (FWHM)
	besmsize	100 μm
Seed Beam	wavelength	267 nm
	NIR pulse duration	~50 fs (FWHM)
	UV pulse duration	250-280 fs (FWHM)
	UV Rayleigh length	1.5-3 m
	UV waist w_0	660 μm

PERFORMANCE OF HGHG SEEDING

Since 2015, the sFLASH experiment has been dedicated to the HGHG seeding scheme. Future experiments will focus not only on HGHG, but also on the more advanced scheme of EEHG [24]. In the following, the performance of HGHG at the sFLASH experiment are presented. The typical parameters used during the HGHG seeding are reported in Tab 1. The energy spread of the uncompressed electron beam after the interaction with the seed laser can be measured for different seed laser pulse intensities and the maximum experimentally achievable modulation amplitude was found to be (350 ± 50) keV. Figure 2(a) shows a recorded TDS measurement of the (uncompressed) electron bunch longitudinal phase space distribution. From this, the energy spread profile along the electron bunch is extracted and fitted with a Gaussian (Fig. 2(b)).

In Fig. 3, consecutive single-shot spectra of the FEL at the 8$^{\mathrm{th}}$ harmonic are presented. The resulting central wavelength is $\lambda_8 = 33.47$ nm and the spectral width is $\Delta\lambda/\lambda_8 = 3.02 \times 10^{-4}$ in FWHM. At the 7$^{\mathrm{th}}$ ($\lambda_7 = 38$ nm) the FWHM spectral

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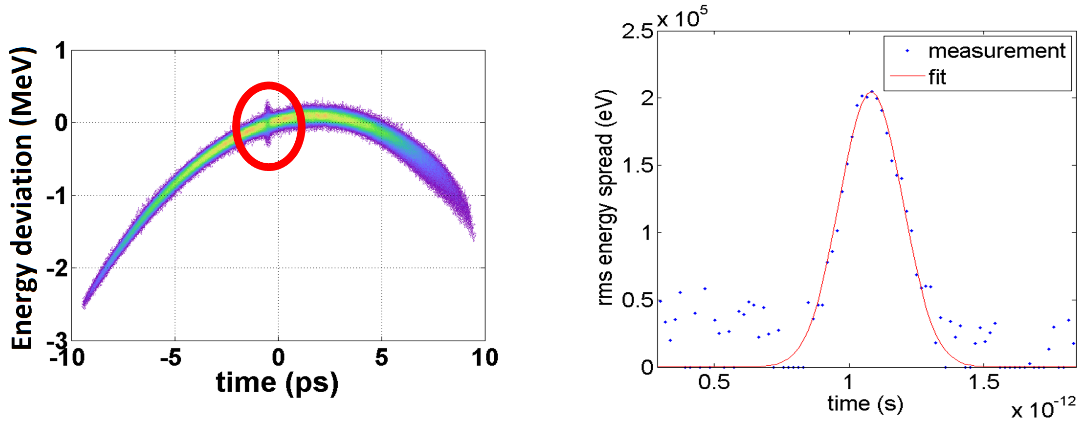

Figure 2: Extraction of modulation amplitude from longitudinal phase-space distribution: (a) Measured longitudinal phase space distribution of an uncompressed electron beam and radiator off. Energy-modulated region is highlighted with a red circle. (b) Extracted rms energy spread along the electron bunch from the measurement shown in (a).

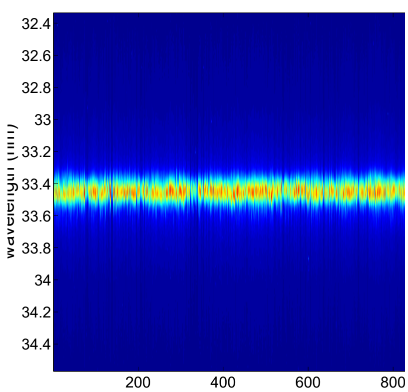

Figure 3: Series of consecutive single-shot FEL spectra taken in HGHG operation at the 8th harmonic.

width is $\Delta\lambda/\lambda_7 \leq 1.4 \times 10^{-3}$. In Fig. 4, a Gaussian is fitted to a single-shot FEL power profile at the 7$^{\text{th}}$ harmonic. From a statistical analysis of a set of profiles at the same harmonic, the duration of the FEL pulse is found to be $\sigma_{t,\mathrm{FEL}} = (28.4 \pm 5.6)$ fs.

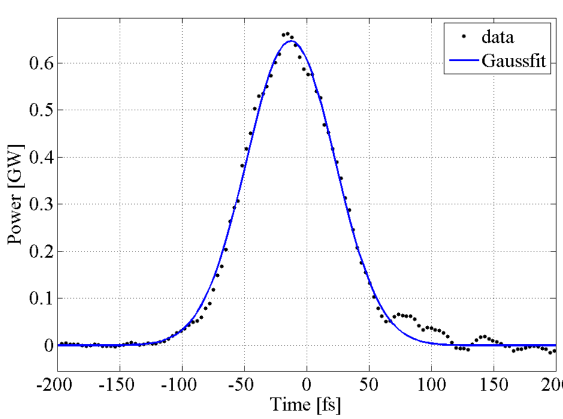

Figure 4: FEL power profile at the 7$^{\text{th}}$ harmonic extracted from TDS measurement.

At sFLASH, seeded FEL radiation up to the 11$^{\text{th}}$ harmonic of the 266 nm seed laser has been observed.

Considerations on EEHG seeding

As reported in [16], an EEHG experiment is currently prepared at sFLASH. After the laser upgrade, two UV-seed laser pulses are available, and by proper configuration of the telescopes the laser pulses can be focussed independently, which enables optimum laser-electron coupling in both modulators.

Presently, further simulations are on-going in order to find the experimental parameters that will give the best performance for the parameters of the sFLASH experiment.

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