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SEEDING R&D AT sFLASH*

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Abstract

Free-electron lasers (FELs) based on the self-amplified spontaneous emission (SASE) principle generate photon pulses with typically poor longitudinal coherence. FEL seeding techniques greatly improve longitudinal coherence by initiating FEL amplification in a controlled way using coherent light pulses. The sFLASH experiment installed at the FEL user facility FLASH at DESY in Hamburg is dedicated to the study of external seeding techniques. In this paper, the layout of the sFLASH seeding experiment is presented and an overview of recent developments is given.

INTRODUCTION

The exponential amplification process in soft and hard x-ray free-electron lasers (FELs) is typically initiated by spontaneous undulator radiation generated by the high-brightness electron bunches at the beginning of the undulator. This stochastic start-up of FELs based on the self-amplified spontaneous emission (SASE) principle results in poor longitudinal coherence.

In the seeded mode of operation, the FEL amplification process is initiated by coherent light pulses generated in an external source. At sFLASH, the high-gain harmonic generation (HGHG) [1] seeding scheme is employed.

The seeding experiment sFLASH is installed in the FLASH1 beamline of the FEL user facility FLASH [2], which has been in user operation since 2005 [3], now delivering SASE FEL radiation down to 4.1 nm [4]. The superconducting linear accelerator of the FLASH facility can generate a maximum of 5000 electron bunches per second for user experiments, which can be distributed between the beamlines FLASH1 and FLASH2 or the plasma wakefield acceleration experiment FLASHForward [5] using a flat-top kicker and a Lambertson DC septum [2], enabling flexible parallel operation of the beamlines [6–8].

THE sFLASH EXPERIMENT

The essential components of the seeding experiment sFLASH are shown in Fig. 1, their parameters are listed in Tab. 1. The electron bunches arriving from the energy collimation section of the FLASH1 electron beamline can interact with ultraviolet seed pulses in two electromagnetic wigglers [9] (M_1 and M_2 in Fig. 1). After each of these so-called modulators, a four-dipole chicane is installed (C_1 and C_2). For HGHG-seeded FEL operation, modulator M_2 and chicane C_2 are used. The seeded electron bunches then enter the 10-meter-long variable-gap radiator system [10] where FEL emission at the desired harmonic takes place. After extraction from the electron beamline, the generated light pulses are either transported to the in-tunnel photon diagnostics (photon energy detectors; Ce:YAG fluorescence screens; spectrometer with $\lambda/\Delta\lambda \approx 500$) or to a photon diagnostics laboratory outside of the accelerator tunnel. There, the seeded FEL pulses can be analyzed in a THz streaking [11] setup by overlapping them with the THz field from a source driven by the seed laser system. At a second beamline in the photon diagnostics laboratory, a reflective extreme ultraviolet (XUV) pulse shaper [12] is currently being set up.

The longitudinal phase-space distribution of the electron bunches is diagnosed by virtue of a transverse-deflecting

Table 1: Experimental Parameters

parameter	**value**
modulators	
period length	200 mm
number of periods	5
maximum K value	10.8
radiator	
number of modules	3 / 1
length of module	2 m / 4 m
period length	31.4 mm / 33 mm
maximum K value	2.72 / 3.03
chicanes	
R_{56} of C_1 (for HGHG)	0 µm
R_{56} of C_2 (for HGHG)	<150 µm
electron bunches	
beam energy	680 – 700 MeV
typ. peak current	0.6 kA
bunch charge	0.4 nC
bunch duration	>500 fs (fwhm)
seed laser pulses	
UV wavelength (seed 1/2)	269 nm/270 nm
UV pulse energy	0.40 – 0.50 mJ
approx. UV pulse duration	100 – 400 fs (fwhm)
approx. NIR pulse duration	40 – 50 fs (fwhm)

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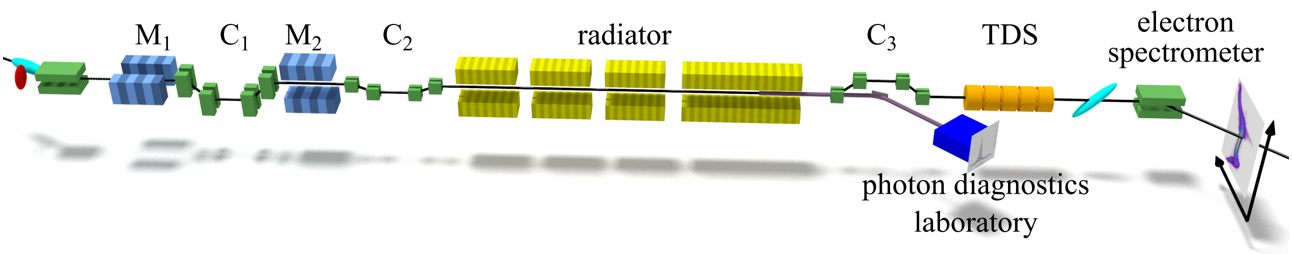

Figure 1: Schematic layout of the sFLASH seeding experiment. The electron beam travels from left to right. See text for further details.

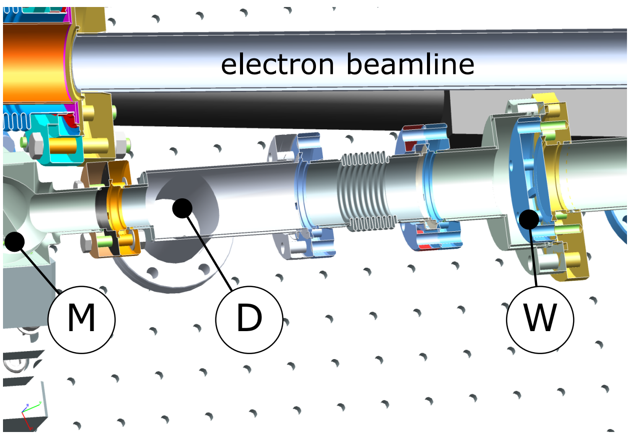

Figure 2: Cross-section of the upgraded sFLASH laser injection beamline. The electron beam travels from left to right in the electron beamline. The second dipole of the FLASH1 energy collimator dogleg is to the right of the shown beamline section. The laser beam is directed onto the electron beam axis in the modulator by the final transport mirror (M) before it is transmitted through the vacuum window (W), which is the interface between laser transport vacuum (on the left side) and accelerator vacuum (on the right side) [13].

structure (TDS) in combination with a dipole spectrometer. The signatures of the laser-electron interaction are routinely used to control the sub-picosecond laser-electron timing, but measured longitudinal phase-space distributions were also used to study the lasing of the seeded FEL [14].

A dedicated near-infrared (NIR) Ti:sapphire laser system (central wavelength 810 nm, FWHM bandwidth ~ 35 nm) in a laboratory adjacent to the accelerator tunnel drives a third-harmonic generation (THG) process in one (for HGHG) or two (for development of EEHG, see below) ultraviolet seed sources. The relative timing as well as the energy of the two seed pulses can be independently controlled. Finally, the seed pulses of orthogonal polarization are combined spatially in a thin-film polarizer before they are injected into the evacuated transport beamline to the interaction regions in the modulators. The maximum ultraviolet seed pulse energy at the entrance window to the evacuated transport beamline is in the range of 0.40 mJ – 0.50 mJ.

Seed Laser Injection

The sFLASH seed laser injection beamline was upgraded during the FLASH shutdown in June/July 2019. Figure 2 shows the newly installed section of this beamline. Up to now, the thin vacuum window (made from crystalline quartz) separating the accelerator vacuum from the vacuum of the transport beamline was before the final transport mirror (which directs the laser pulses onto the electron beam axis in the modulator) and the two screen stations used to diagnose the seed laser beam. The vacuum window is now installed after the final mirror, resulting in several improvements: Firstly, all optical components of the seed laser transport system are no longer in accelerator vacuum, making them readily accessible for maintenance. Secondly, the seed laser radiation can be extracted for (online) diagnostic purposes between the last mirror and the interaction region. The installation of additional seed laser diagnostics (at position (D) in Fig. 2) is currently being prepared. In the course of this upgrade, the vacuum chambers containing the seed injection and focusing system [15] originally installed for the experiments that demonstrated direct-HHG seeding at 38 nm [16, 17] were removed.

Laser-electron interaction was already achieved with the upgraded hardware. Seeded FEL operation at the sFLASH experiment is to be re-commissioned in fall 2019.

Upgrade Plans for the First Chicane

The advanced seeding scheme echo-enabled harmonic generation (EEHG) [18] enables the efficient generation of bunching at high harmonics. Compared to HGHG seeding, EEHG adds less energy spread to the electron beam and imperfections of the electron beam have reduced impact on the parameters of the generated photons (see [19] for a simulation study for HGHG). EEHG-seeded FEL operation was recently demonstrated at the seeded FEL user facility FERMI at wavelengths down to 5.9 nm (harmonic 45 of the 264-nm seed laser) [20].

At high harmonics, this promising seeding scheme calls for a significant overshearing of the longitudinal phase-space distribution of the incoming electron beam in the first modulator-chicane section. However, the accessible R_{56} range of the currently installed first chicane (C_1 in Fig. 1) is limited both by the first field integral of the chicane dipoles as well as the inner diameter of the vacuum chamber, restricting

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the accessible parameter space [21, 22]. To overcome these limitations, an upgrade of the first sFLASH chicane was engineered and is being prepared. This upgrade comprising a flat vacuum chamber and new dipole magnets aims at longitudinal dispersions of about 6 millimeters at an electron beam energy of 700 MeV.

SUMMARY AND OUTLOOK

The seeding experiment sFLASH is installed at the FEL user facility FLASH. Recently, HGHG-seeded FEL operation was mainly performed at the 7th and 8th harmonic of the ultraviolet seed laser. In summer 2019, the seed laser injection beamline was upgraded enabling development of seed laser diagnostics techniques which is important in view of the envisioned FLASH2020+ upgrades [23, 24]. The laser-electron interaction was recommissioned and we plan to re-establish seeded FEL operation in fall 2019. Currently, an upgrade of the first chicane is being prepared, lifting present restrictions of the parameter space of EEHG seeding.

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