STATUS OF THE sFLASH EXPERIMENT*

C. Lechner†, R. W. Assmann, J. Bödewadt, V. Grattoni, I. Hartl,
M. M. Kazemi, T. Laarmann, A. Przystawik, DESY, 22607 Hamburg, Germany
S. Khan, T. Plath, DELTA, TU Dortmund University, 44227 Dortmund, Germany
A. Azima, H. Biss, M. Drescher, W. Hillert, L. L. Lazzarino, V. Miltchev,
J. Rossbach, University of Hamburg, 22761 Hamburg, Germany

Abstract

The sFLASH experiment at the free-electron laser (FEL) FLASH1 is a setup for the investigation of external FEL seeding. Since 2015, the seeding scheme high-gain harmonic generation (HGHG) is being studied. At the end of the seeded FEL, an RF deflector enables time-resolved analysis of the seeded electron bunches while the photon pulses can be characterized using the technique of THz streaking. In this contribution, we present the current configuration of the experiment and give an overview of recent experimental results.

INTRODUCTION

Free-electron lasers (FELs) deliver photon pulses of unparalleled brilliance. In the soft and hard x-ray wavelength ranges, the exponential amplification process in these devices is typically initiated by spontaneous undulator radiation emitted as the high-brightness electron bunch enters the undulator. This stochastic start-up in the so-called self-amplified spontaneous emission (SASE) mode of operation entails poor longitudinal coherence of the generated photon pulses.

To initiate the FEL process in a well-controlled way, so-called seeding techniques were conceived. Here, the FEL amplification process is initiated and controlled by coherent light pulses from an external source. At sFLASH, we currently study the high-gain harmonic generation (HGHG) seeding scheme [1].

The seeding experiment sFLASH is installed at the FLASH1 beamline of the FEL user facility FLASH [2], which has been in operation since 2005, delivering high-brilliance SASE FEL radiation down to 4.2 nm. The superconducting linear accelerator generates high-brightness electron bunches with energies up to 1.25 GeV in bursts of up to 800 electron bunches (at a 1-MHz repetition rate) with 10 bursts per second. The electron bunches are distributed over the undulator beamlines FLASH1 and FLASH2 using a flat-top kicker and a Lambertson DC septum [2]. This enables FEL operation in both undulator beamlines at the full 10-Hz repetition rate of the linear accelerator [3–5].

EXPERIMENTAL SETUP

Figure 1 shows the essential components of sFLASH, their parameters are compiled in Table 1. The electron bunches

Table 1: Experimental Parameters

parameter	**value**
modulators	
period length	0.2 m
effective length	1.2 m
maximum K value	10.8
radiator	
period length	31.4 mm
effective length	10 m
maximum K value	2.7
chicanes	
R_{56} of C_1 (for HGHG)	0 µm
R_{56} of C_2 (for HGHG)	<150 µm
electron bunches	
energy	680 – 700 MeV
typ. peak current	600 A
bunch charge	0.4 nC
bunch duration	>500 fs (fwhm)
seed laser pulses	
wavelength	267 nm
pulse energy	500 µJ
NIR pulse duration	∼ 50 fs (fwhm)
UV pulse duration	250 – 280 fs (fwhm)

arriving from the linear accelerator and the seed laser pulses interact in two electromagnetic wigglers with 5 full periods [6, 7] (M_1 and M_2 in Fig. 1) of orthogonal polarization. After each wiggler, a 4-dipole chicane is installed (C_1 and C_2 in Fig. 1). In the subsequent, 10-m-long variable-gap radiator, FEL emission takes place. The resulting light pulses are extracted from the electron beamline and can be transported either to in-tunnel photon diagnostics (energy detector, fluorescence screens, and a spectrometer with $\lambda/\Delta\lambda \approx 500$) or to a photon diagnostics laboratory outside of the accelerator tunnel. The longitudinal phase space of the electron bunches can be diagnosed with the combination of a transverse-deflecting structure (TDS) and an energy spectrometer.

Seed Laser System

For seeding experiments, a dedicated near-infrared (NIR) Ti:sapphire laser system is available. The 267-nm ultraviolet (UV) seed laser pulses are generated by third-harmonic generation (THG) from the 800-nm laser pulses.

* Work supported by Federal Ministry of Education and Research of Germany under contract No. 05K13GU4, 05K13PE3, and 05K16PEA.
† christoph.lechner@desy.de

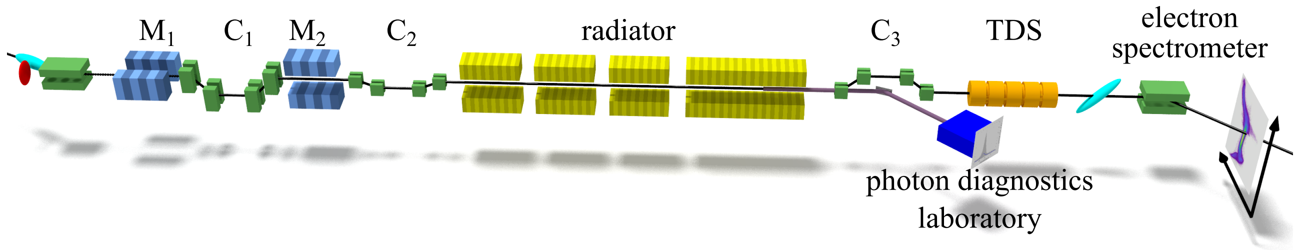

Figure 1: Layout of the sFLASH seeding experiment.

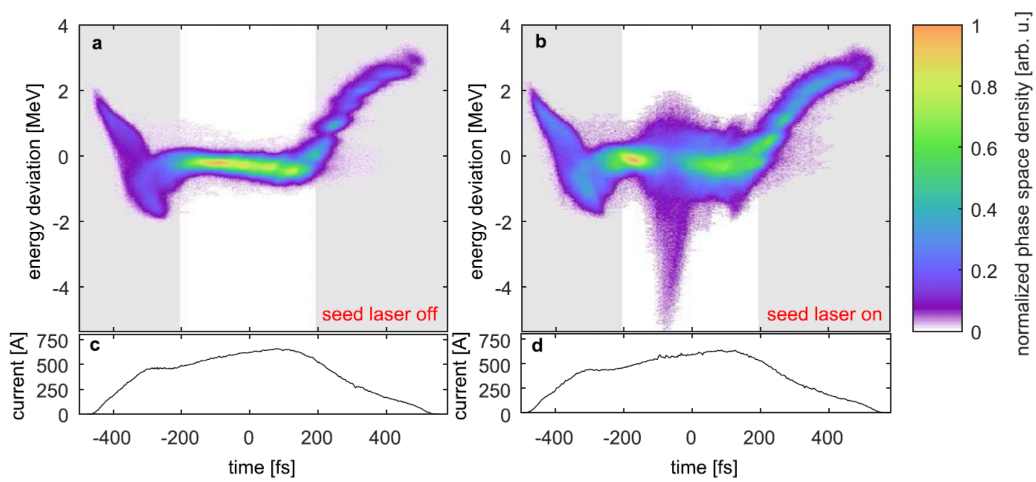

Figure 2: Longitudinal phase-space distributions of electron bunches measured with the transverse-deflecting structure installed downstream of the sFLASH radiator. The reference bunches *(a)* were acquired with seed laser off. With seed laser on, the signature of the FEL lasing (here at the 7th harmonic) is clearly visible in the longitudinal phase-space distribution *(b)*. Reprinted from [9] under the Creative Commons Attribution 4.0 International License [10].

At the entrance to the in-vacuum transport to the modulator, the maximum UV pulse energy is 500 µJ. The longitudinal position of the beam waists in the electron beamline is controlled by UV telescopes and the waist position and size are diagnosed by means of Ce:YAG fluorescence screens installed around M$_2$.

TIME-RESOLVED CHARACTERIZATION OF SEEDED FEL PULSES

With sFLASH in HGHG-seeded operation (using modulator M$_2$ and chicane C$_2$), we implemented two methods to diagnose the longitudinal photon pulse profile: TDS-based analysis of the seeded electron bunches leaving the radiator and THz streaking of the photon pulses.

Analysis of the Seeded Electron Bunches

The exponential FEL amplification process alters the longitudinal phase-space distribution of the electron bunch. Comparing longitudinal phase-space distributions acquired with and without FEL lasing enables to extract the longitudinal power profile of the photon pulse on a single-shot basis. This was first demonstrated at the SASE FEL LCLS [8]. At sFLASH, this technique was applied for the first time at a seeded FEL [9]. Without a seed laser pulse, the 10-m-long radiator operates as SASE FEL, extracting only a negligible amount of energy from the bunches (Fig. 2(a)). In Fig. 2(b), the signature of FEL lasing selectively initiated by the seed laser pulse is clearly visible. This energy drop of the electrons reveals the power profile of the FEL pulse. Scanning the seed over the bunch enables local sampling of the lasing performance within the electron bunch [9].

THz Streaking of Photon Pulses

The seeded FEL pulses can also be studied using THz streaking, a photon-based analysis technique (see for instance [11]). In the setup realized in the photon diagnostics laboratory [12], the seeded FEL pulse is overlapped in a gas target with a THz pulse produced from a fraction of the NIR pulses driving the UV seed source. This translates the longitudinal information of the photon pulse into a photoelectron spectrum that is acquired with a time-of-flight spectrometer.

Comparison of the two Techniques

Using these techniques, seeded FEL pulses at the 8th harmonic (wavelength 33.4 nm) were analyzed [12]. With the TDS-based analysis of the electron bunch, a pulse duration of (57 ± 14) fs was found while with THz streaking we determined the pulse duration to be (54 ± 7.5) fs. Moreover, THz streaking provides access to the optical phase of the seeded

FEL pulses and the average chirp of the seeded FEL pulses was found to be (-1940 ± 800) THz/ps [12].

Towards Tailored Seeded FEL Pulses

In a simulation study carried out using the FEL code Genesis [13], the impact of additional group-delay dispersion (GDD) acting on the seed laser pulses on the properties of the HGHG-seeded photon pulses was studied [14].

SUMMARY AND OUTLOOK

At the seeding experiment sFLASH, two analysis methods revealing longitudinal properties of the generated light pulses were applied to an HGHG-seeded FEL operating at 33.4 nm. The results obtained from a TDS-based analysis of the electron bunches leaving the undulator and using THz streaking of the photon pulses were found to be in good agreement. The analyzed seeded photon pulses exhibit an average chirp of (-1940 ± 800) THz/ps.

The already existing hardware offers numerous research opportunities: Seeded electron bunches can be transported from the sFLASH section to the entrance of the FLASH1 main undulator. This would enable seeded operation of the fixed-gap FLASH1 main undulator [15]. Moreover, first studies of the advanced seeding scheme echo-enabled harmonic generation (EEHG) [16] are under preparation. Currently, the relatively low longitudinal dispersion R_{56} of the first chicane (C_1) is limiting the accessible parameter space [17]. To lift these restrictions, an upgrade of this chicane aiming at $R_{56} \approx 4$ mm at 700 MeV is being engineered.

ACKNOWLEDGEMENTS

Without the help from many groups at DESY, the preparation and commissioning of all components of the seeding experiment would not have been conceivable. Their support is gratefully acknowledged.

REFERENCES

[1] L.H. Yu, “Generation of intense uv radiation by subharmonically seeded single-pass free-electron lasers”, *Phys. Rev. A*, vol. 44, p. 5178, 1991.

[2] M. Vogt *et al.*, “Status of the Superconducting Soft X-Ray Free-Electron Laser FLASH at DESY”, presented at the 9th Int. Particle Accelerator Conf. (IPAC’18), Vancouver, BC, Canada, Apr. 2018, paper TUPMF090, this conference.

[3] B. Faatz *et al.*, “Simultaneous operation of two soft x-ray free-electron lasers driven by one linear accelerator”, *New J. Physics*, vol. 18, p. 062002, 2016.

[4] J. Rönsch-Schulenburg *et al.*, “Experience with Multi-Beam and Multi-Beamline FEL-Operation”, in *Proc. 8th Int. Particle Accelerator Conf. (IPAC’17)*, Copenhagen, Denmark, May 2017, pp. 2621–2624.

[5] T. Plath *et al.*, “Free-electron laser multiplex driven by a superconducting linear accelerator”, *J. Synchrotron Radiation*, vol. 23, p. 1070, 2016.

[6] G. Angelova *et al.*, “Installation of the Optical Replica Synthesizer in FLASH”, in *Proc. 27th Int. Free-Electron Laser Conf. (FEL’07)*, Novosibirsk, Russia, 2007, pp. 438–440.

[7] J. Bödewadt *et al.*, “Experience in Operating sFLASH With High-Gain Harmonic Generation", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC’17)*, Copenhagen, Denmark, May2017, pp. ,2596–2599.

[8] C. Behrens *et al.*, “Few-femtosecond time-resolved measurements of X-ray free-electron lasers’, *Nat Commun.* vol. 5, p. 4762, 2014.

[9] T. Plath *et al.*, “Mapping few-femtosecond slices of ultrarelativistic electron bunches’, *Sci. Rep.*. vol. 7, p. 2431, 2017.

[10] Creative Commons Attribution 4.0 International License, `https://creativecommons.org/licenses/by/4.0/`.

[11] U. Frühling *et al.*, “Single-shot terahertz-field-driven X-ray streak camera", *Nat Photonics*, vol. 3, p. 523, 2009.

[12] A. Azima *et al.*, “Direct measurement of the pulse duration and frequency chirp of seeded XUV free electron laser pulses", *New J. Phys* vol. 20, p. 013010, 2018.

[13] S. Reiche, “GENESIS 1.3: a fully 3D time-dependent FEL simulation code", *Nucl. Instrum. and Meth. A*, vol. 429, p. 243, 1999.

[14] V. Grattoni *et al.*, “Control of FEL Radiation Properties by Tailoring the Seed Pulses", presented at the 9th Int. Particle Accelerator Conf. (IPAC’18), Vancouver, BC, Canada, Apr. 2018, paper TUPMF078, this conference.

[15] V. Grattoni *et al.*, “An Option to Generate Seeded FEL Radiation for FLASH1", presented at the 9th Int. Particle Accelerator Conf. (IPAC’18), Vancouver, BC, Canada, Apr. 2018, paper TUPMF079, this conference.

[16] G. Stupakov, “Using the Beam-Echo Effect for Generation of Short-Wavelength Radiation", *Phys. Rev. Lett* vol. 102, p. 074801, 2009.

[17] J. Bödewadt *et al.*, “Parameter Optimization for Operation of sFLASH With Echo-Enabled Harmonic Generation", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC’17)*, Copenhagen, Denmark, May 2017, pp. 2592–2595.