EXPERIENCE IN OPERATING sFLASH WITH HIGH-GAIN HARMONIC GENERATION*

J. Bödewadt†, R. Aßmann, N. Ekanayake‡, B. Faatz, I. Hartl,
M. M. Kazemi, T. Laarmann, C. Lechner, A. Przystawik , DESY, 22607 Hamburg, Germany
Ph. Amstutz, A. Azima, M. Drescher, W. Hillert, L. L. Lazzarino, Th. Maltezopoulos§, V. Miltchev,
T. Plath, J. Roßbach, University of Hamburg, 22671 Hamburg, Germany
K. Hacker, S. Khan, N. Lockmann, R. Molo, TU Dortmund University, 44227 Dortmund, Germany

Abstract

sFLASH, the experimental setup for external seeding of free-electron lasers (FEL) at FLASH, has been operated since 2015 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. FEL saturation was reached for the 7th harmonic of the 267 nm seed laser. In this contribution, we present the latest experimental results.

INTRODUCTION

Fully coherent radiation in the extreme ultraviolet (XUV), soft-, and hard X-ray spectral range is a key ingredient for studying the dynamics and structure of matter on the atomic and molecular level and for time scales in the order of atto- and femtoseconds. In combination with the demand for highest spectral brightness, this lead to the development of free-electron lasers (FEL) [1–4]. These devices have been operated for more than a decade now, using the principle of self-amplified spontaneous emission (SASE) [5, 6]. In this operation mode, the FEL radiation has a high degree of transverse coherence but it suffers from a typically poor longitudinal coherence due to the stochastic shot-noise, which is the startup source for the SASE amplification process. In contrast to that, an external seed source which initiates the FEL process allows to maintain the good coherence properties of the seed. Two different schemes for FEL seeding have been proposed and demonstrated in the past: Firstly those, which manipulate the electron bunch distribution such that a strong microbunching is created at the seed wavelength. The harmonic content of the density modulation is able to drive the FEL at high harmonics as in the “high-gain harmonic generation” (HGHG) [7] and the “echo-enabled harmonic generation” (EEHG) [8] seeding schemes. Secondly those, which initiate the FEL process directly at the target wavelength. Seed sources are either a high-harmonic generation (HHG) [9] source driven by conventional lasers (HHG seeding) [10] or a SASE FEL with a subsequent monochromator in so-called self-seeding schemes [11].

The FEL facility in Hamburg, FLASH, at DESY has been operated since 2005 as a FEL user facility in SASE mode [1]. The wavelength range has been upgraded in several steps to cover a range from ~4.1 nm to 45 nm at the beamline FLASH1. In addition, a second undulator beamline, called FLASH2, was build and commissioned recently to increase the amount of beamtime for users in the future [12]. In 2010, an experimental setup for seeding developments has been installed upstream of the FLASH1 main SASE undulator [13]. At this setup, the direct HHG seeding at 38 nm was demonstrated in 2012 [14]. A limited contrast ratio as well as the fact that the hit rate of the external pulses with the electron bunches was dominated by the relative arrival time variations, which were in the order of the pulse durations, lead to the decision to set the focus of the seeding R&D at FLASH on HGHG and EEHG seeding [15, 16]. The results of the sFLASH seeding experiment guide the design process of the proposed FLSAH2 seeding option [17]. Other facilities have demonstrated self-seeding for photon wavelength below 1.8 nm [18, 19] and HGHG seeding for wavelength between 4 nm and 80 nm [20]. Using the principle of EEHG, seeded undulator radiation up to the 75th harmonic of the seed laser wavelength has been demonstrated [21].

In the following, we will describe the experience with HGHG seeding at sFLASH and the current status of the FEL seeding developments at DESY.

EXPERIMENTAL SETUP

The Seeding Section in FLASH1

Figure 1 shows a schematic layout of the sFLASH seeding experiment. An overview of the FEL user facility FLASH can be found in [22]. After the energy collimator, the seeding section starts with two short electro-magnetic wigglers (labeled as MOD1 and MOD2) with 5 full periods [23] each followed by a magnetic chicane (labeled as C1 and C2). Four variable-gap undulators (labeled as RAD) with an effective length of 10 m act as the FEL radiators. The FEL pulses are guided to an in-tunnel photon diagnostics section or to a dedicated photon diagnostic hutch outside of the radiation shielding using a mirror assembly. The chicane C3 steers the electron beam around the extraction mirrors. A subsequent transverse-deflecting structure (TDS) and a dispersive

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† contact: joern.boedewadt@desy.de
‡ present address: Michigan State University, East Lansing, MI 48824, USA
§ present address: European XFEL GmbH, 22869 Schenefeld, Germany

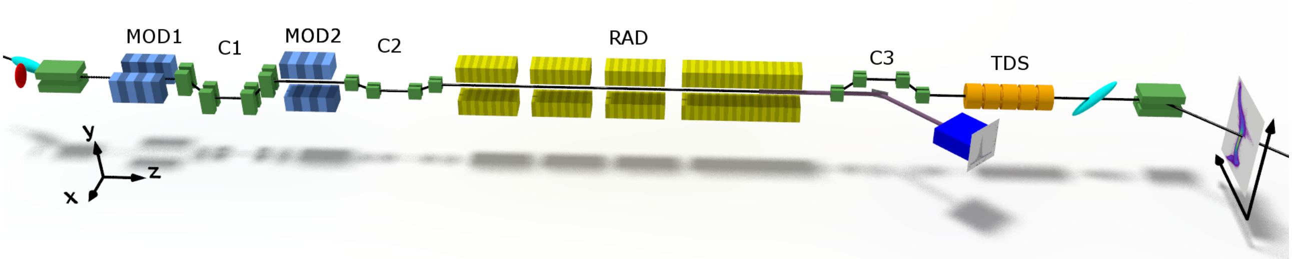

Figure 1: Layout of the sFLASH seeding experiment.

beam dump section allows to diagnose the longitudinal phase space distribution of the electron bunches.

The Seed Laser

The 267-nm seed pulses are generated by third-harmonic generation (THG) of near-infrared (NIR) Ti:sapphire laser pulses. The maximum energy of the 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 2.3 m. A single-shot cross-correlator for NIR and UV pulses allows to measure the UV pulse duration in the laser laboratory. The NIR pulse duration is simultaneously measured with an single-shot auto-correlator. The longitudinal position of the beam waist can be adjusted by changing the NIR focusing into the THG setup. The seed beam position and size is measured before and after MOD2 using fluorescence screens.

The FEL Diagnostics

To diagnose the seeded FEL radiation, different detectors are available: A fluorescence screen for transverse beam diagnostics, a photon flux monitor based on a microchannel plate, and a high-resolution spectrometer ($\lambda/\Delta\lambda \approx 500$) for wavelengths from 4 to 40 nm [24]. In addition, the FEL beam can be transported to a dedicated diagnostics laboratory outside the radiation shielding of the accelerator. Here, the temporal profile of the FEL pulse can be studied utilizing a photon-based streaking technique [25, 26]. Using the TDS, single-shot information about the FEL photon pulse can be extracted by analysing the longitudinal phase space distribution of the individual electron bunches [27].

HGHG EXPERIMENT

In the last two years, the sFLASH setup was operated with a single UV seed laser pulse to generate coherent harmonic generation (CHG) radiation and HGHG FEL radiation. Most of the time, the second modulator (MOD2) was used to imprint the energy modulation and chicane C2 was used for bunching. Table 1 shows the operation parameters. The laser-induced energy modulation is characterized with the TDS and a maximum achievable modulation amplitude of 350±50 keV was demonstrated, consistent with the seed laser power present in the modulator. For these measurements, the

Table 1: Experimental Parameters

	parameter	value
modulator	period length	0.2 m
	effective length	1.2 m
	max. K_{peak}	10.8
radiator	period length	31.4 mm
	effective length	10 m
	max. K_{peak}	2.7
chicanes	R_{56} C1	0 µm
	R_{56} C2	50-200 µm
	R_{56} C3	190 µm
electron beam	energy	680-700 MeV
	typ. peak current	700 A
	charge	0.4 nC
	bunch duration	>500 fs (fwhm)
seed beam	wavelength	267 nm
	pulse energy	<280 µJ
	NIR pulse duration	~50 fs (fwhm)
	UV pulse duration	250-280 fs (fwhm)
	UV Rayleigh length	1.6 m

electron bunch is operated at minimum compression to minimize effects driven by longitudinal space-charge forces [28]. For HGHG operation, the electron bunch was compressed to achieve peak currents of up to 700 A. Figure 3 shows a histogram of seeded FEL pulse energies after setting all radiators to 33.4 nm (8th harmonic of the seed wavelength). Single-shot spectra are presented in Figure 4. The average seeded FEL pulse energy is about 26 µJ for the 8th harmonic and 50 µJ for the 7th harmonic. At the 7th harmonic, the FEL gain length was measured to be between 0.6 and 0.9 m depending on the initial modulation amplitude.

SUMMARY

Recently, the seeding experiment at FLASH has been operated in the HGHG mode with a seed wavelength of 267 nm and lasing at the 7th, 8th, and 9th harmonic. The laser-induced energy modulation was characterized with a TDS and is in good agreement with the expected values. A detailed characterization of the FEL performance was carried out using time-resolved diagnostic methods.

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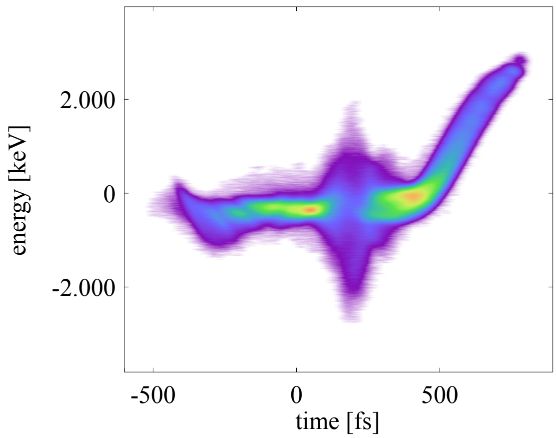

Figure 2: Longitudinal phase-space distribution measured after the seeding setup. The region with increased slice energy spread is the signature of the successful laser-electron interaction.

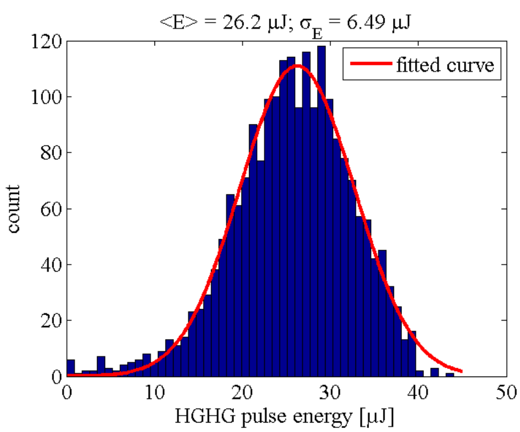

Figure 3: Histogram of seeded FEL pulse energies at the 8th harmonic of the UV seed laser.

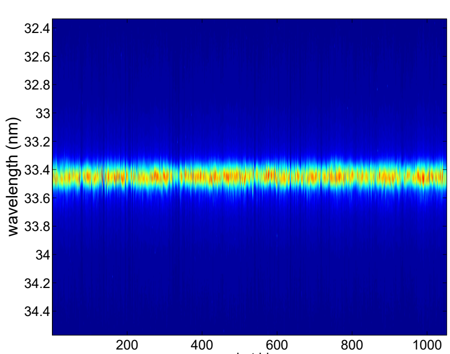

Figure 4: Series of about 1000 consecutive single-shot FEL spectra taken in HGHG operation at the 8th harmonic.

OUTLOOK

The sFLASH setup will be further used for HGHG operation to perform characterization of the photon pulse properties. Currently, an upgrade of the seed laser setup is in progress for the preparation of EEHG seeding [29].

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