# RECENT RESULTS FROM FEL SEEDING AT FLASH*

J. Bödewadt†, S. Ackermann, R. Aßmann, N. Ekanayake, B. Faatz, G. Feng, I. Hartl, R. Ivanov, T. Laarmann, J. Mueller, T. Tanikawa, DESY, Hamburg, Germany
Ph. Amstutz, A. Azima, M. Drescher, L. Lazzarino, C. Lechner, Th. Maltezopoulos, V. Miltchev, T. Plath, J. Roßbach, University of Hamburg, Germany
K. Hacker, S. Khan, R. Molo, DELTA, Dortmund, Germany

*Abstract*

The free-electron laser facility FLASH at DESY operates since several years in SASE mode, delivering high-intensity FEL pulses in the extreme ultraviolet and soft x-ray wavelength range for users. In order to get more control of the characteristics of the FEL pulses, external FEL seeding has proven to be a reliable method to do so. At FLASH, an experimental setup to test several different external seeding methods has been installed since 2010. After successful demonstration of direct seeding at 38 nm, the setup is now being operated in HGHG and later in EEHG mode. Furthermore, other studies on laser-induced effects on the electron beam dynamics have been performed. In this contribution, we give an overview of recent experimental results on FEL seeding at FLASH.

## INTRODUCTION

Fully coherent radiation in the extreme ultra-violet (XUV), soft-, and hard X-ray spectral range is highly demanded for a variety of scientific fields. 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 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 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] operation modes. 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].

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† contact: joern.boedewadt@desy.de

The FEL facility in Hamburg, FLASH, at DESY is operated since 2005 as a user facility in SASE mode [1]. Since 2010, an experimental setup for seeding developments has been installed prior to the main SASE undulator of the FLASH1 [12]. At this setup, the direct HHG seeding at 38 nm was demonstrated in 2012 [13]. 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 [14, 15]. Other facilities have demonstrated self-seeding for photon energies above 700 eV [16, 17] and HGHG seeding for wavelength between 4 nm and 80 nm [18]. The EEHG principle has been demonstrated for wavelength down to ≈170 nm [19]. In the following, we will describe 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 FLASH1 FEL beamline. An overview of the entire FLASH facility can be found in [20]. After the energy collimator, the seeding section starts with two short electro-magnetic wigglers (labeled MOD1 and MOD2) with 5 full periods [21] each followed by a magnetic chicane C1 and C2. Four variable-gap undulators with an effective length of 10 m act as the FEL radiators. The FEL pulses are guided to a photon diagnostics section using a mirror system. The chicane C3 steers the electron beam around the extraction mirrors. The following transverse deflecting structure (TDS) and a dispersive dump section allows to diagnose the longitudinal phase space distribution of the electron bunches.

### *The Seed Laser*

The 266-nm seed pulses are generated by third-harmonic generation (THG) of near-infrared (NIR) Ti:sapphire laser pulses. The UV pulse energy at the interaction region with the electron bunch can be set up to 280 $\mu$J, the Rayleigh length is about 1.4 m. The longitudinal position of the beam waist can be adjusted by changing the NIR focusing into the THG setup. To relax the tolerance of the transverse laser-electron overlap, the waist has been set about 1 m after the end of undulator MOD2. The seed beam position and size is measured before and after MOD2 using fluorescence screens.



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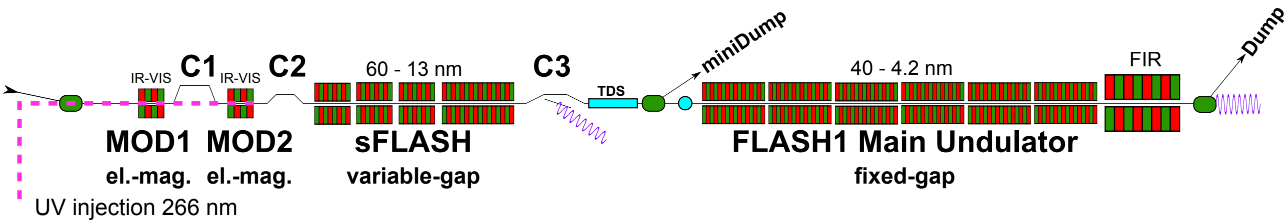


Figure 1: Layout of the FLASH1 beamline.

### *The FEL Diagnostics*

To diagnose the seeded FEL radiation, there are different detectors available: A fluorescence screen for transverse beam diagnostics, an MCP-based photon flux monitor, and a high-resolution spectrometer ($\lambda/\Delta\lambda \approx 700$) for wavelengths from 4 to 40 nm [22]. In addition, the FEL beam can be transported to a dedicated diagnostics laboratory outside the radiation shielding of the accelerator. Here, the temporal FEL profile is going to be studied utilizing the photon-based streaking technique [23, 24].

Table 1: Experimental Parameters

| | parameter | value |
|---|---|---|
| **modulator** | period length | 0.2 m |
| | eff. length | 1.2 m |
| | K (peak) | <10 |
| **radiator** | period length | 31.4 mm |
| | eff. length | 10 m |
| | K (peak) | <2.7 |
| **chicanes** | $R_{56}$ C1 | 0 $\mu$m |
| | $R_{56}$ C3 | 70 $\mu$m |
| | $R_{56}$ C2 | 190 $\mu$m |
| **electron-beam** | energy | 700 MeV |
| | peak current | 600 A |
| | charge | 0.4 nC |
| | bunch duration | 500 fs (fwhm) |
| **seed-beam** | wavelength | 266 nm |
| | pulse energy | <280 $\mu$J |
| | pulse duration | 120 fs (fwhm) |
| | rayleigh length | 1.6 m |

## HGHG EXPERIMENT

The first step towards EEHG operation is the commissioning of the laser/electron overlap, the characterization of the induced energy modulation, operation of chicanes and radiators, as well as the characterization of the electron beam parameters. For this purpose, the seeding setup is currently operated in the HGHG mode using undulator MOD2 as modulator and chicane C2 for bunching. Table 1 shows the operation parameters. The laser-induced energy modulation is characterized with the TDS. Figure 2 shows a measurement of the longitudinal phase-space distribution for an uncompressed electron bunch as typically used to establish the longitudinal overlap. For stronger electron bunch compression, the induced energy modulation in combination with subsequent longitudinal dispersion is able to trigger an oscillation of energy modulation and bunching driven by the longitudinal space-charge forces [25]. This effect changes the observed slice energy

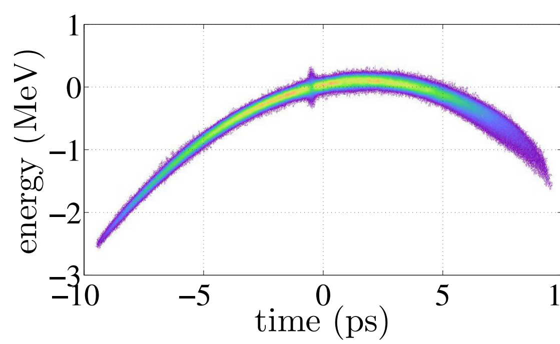


Figure 2: Longitudinal phase-space distribution measured after the seeding setup for an uncompressed electron bunch. The laser-induced energy modulation emerges as a region with larger slice energy spread.

spread at the TDS and has to be considered for the interpretation of the data. The induced energy modulation is 350 ± 50 keV and is consistent with the present seed laser power in the modulator. For HGHG operation, the electron bunch compression was set to 600 A. Figure 3 shows the observed FEL pulse energy for 1000 consecutive shots after setting all radiators to 38 nm (7th harmonic of the seed wavelength). Single-shot spectra are presented in Figure 4. The maximum pulse energy is about 70 $\mu$J which is in good agreement with simulations of the saturation pulse energy performed with GENESIS1.3 [26]. The corresponding gain length from the simulation is 0.85 m. The mean pulse energy was measured to be (12.5 ± 12.2) $\mu$J with a background SASE signal of (2.6 ± 0.2) nJ. The origin for the large fluctuation of 100% has not yet been studied in detail. Possible explanations could be the quality of the laser/electron overlap as a combination of pointing instability and intensity fluctuation of the laser beam or a fluctuation of the electron bunch properties due to microbunching instability.


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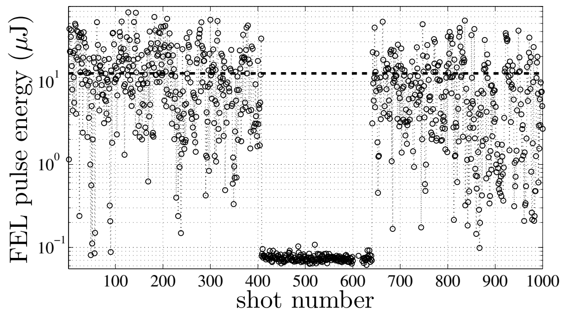


Figure 3: FEL pulse energy of 1000 consecutive shots. Between shot number 400 and 650, the seed laser shutter was closed.

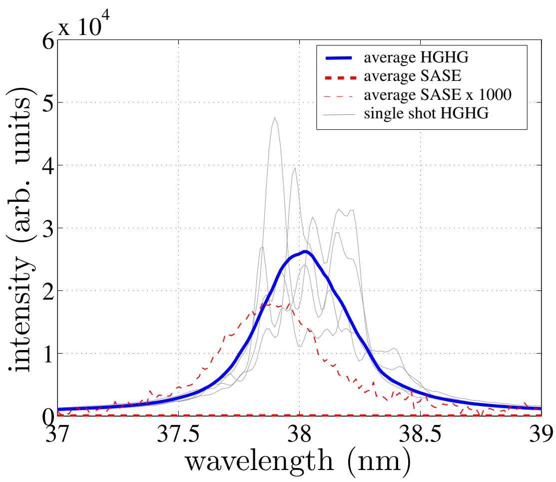


Figure 4: Average of 1000 FEL spectra for HGHG operation (blue solid line) and typical single-shot spectra at the mean pulse energy with HGHG seeding (thin line). The SASE background (red dashed lines) was multiplied by a factor of 1000 for better visibility.

## SUMMARY

Recently, the seeding experiment at FLASH has been operated in the HGHG mode with a seed wavelength of 266 nm and lasing at the 7th harmonic at 38 nm. The laser-induced energy modulation has been characterized with a TDS and is in good agreement with the expected values. Optimization and investigation of the operation performance for electron peak currents of 600 A is ongoing.

## OUTLOOK

During the upcoming study times, the HGHG performance for shorter wavelength as well as higher peak currents will be studied with the goal to characterize the slice energy spread of the electron bunch under different compression schemes. The origin of the large FEL output fluctuations will be investigated. Temporal characterization of the seeded FEL pulses is under preparation. In the second half of 2015, the seed laser injection is planned to be upgraded [27] to allow for the operation of EEHG seeding at a later stage.

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