PARAMETER OPTIMIZATION FOR OPERATION OF sFLASH WITH ECHO-ENABLED HARMONIC GENERATION*

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Abstract

The free-electron laser facility FLASH has a dedicated experimental setup for external FEL seeding applications for the extrem ultraviolet (XUV) and soft x-ray spectral range. Recently, the setup was operated as high-gain harmonic generation FEL. Furthermore, it allows the operation of echo-enabled harmonic generation (EEHG). From the experimental experience with HGHG operation, we revise the initial plans [1] and present here a relaxed set of parameters for operating the sFLASH setup with EEHG.

INTRODUCTION

Free-electron lasers (FELs) are sources for coherent, intense, and ultra-short radiation flashes covering a broad range of the electro-magnetic spectrum from the far-infrared into the hard x-ray spectral domain [2–5]. They enable the study of the structure and dynamics of matter on the atomic and molecular level and on femtosecond time-scales. Besides the high peak-brightness of FEL radiation, the coherence properties of the light are of utmost importance. Though, all FELs utilize a high degree of transverse coherence, the longitudinal coherence of FEL radiation, generated from so-called self-amplified spontaneous emission of radiation (SASE) FELs, is typically poor [6, 7]. In this mode of operation, the light amplification process is started from stochastic noise of the high-relativistic electron bunches and therefore limits the degree of temporal coherence. Other modes of FEL operation make use of an external fully-coherent radiation pulse, which trigger the amplification process. These operation modes are typically referred to as FEL seeding. With that, the coherence properties of the FEL can be significantly improved. On of the challenges for FEL seeding is to cover the full radiation spectrum as it is possible with SASE FELs. A promising technique for FEL seeding is the so-called echo-enabled harmonic generation (EEHG) mode of operation proposed in 2009 [8]. Here, the electron bunches are pre-conditioned for the FEL by manipulating the microscopic charge distribution using external optical laser radiation. By that, a coherent mirco stucture is imprinted inside the electron bunches, utilizing the potential to radiate at high-harmonics of the initial seed laser radiation. For a detailed explanation of the process, we refer to [8] and [9]. A comprehensive review on similar seeding techniques can be found in [10]. Proof-of-principle experiments to generate microbunching with the EEHG technique have been carried out in recent years. Seeded undulator radiation was demonstrated for the 75th harmonic of the initial seed laser wavelength of 2.4 µm [11] and in 2012 an FEL demonstration experiment showed FEL gain at 350 nm, the 3rd harmonic of the initial seed wavelength [12]. FEL lasing at shorter wavelength with this scheme is still pending but is an important step to proof its feasibility before applying this mode of operation to FEL user facilities [13].

At FLASH, an FEL user facility at DESY in Hamburg, an experimental setup for seeding developments, sFLASH, was installed prior to the FLASH main SASE undulator [14] in 2010. After the demonstration of direct FEL seeding at 38 nm [15] the setup is now operated with high-gain harmonic generation (HGHG) seeded by at a wavelength of 267 nm. The experimental hardware in principle also allows for the operation of EEHG. Tolerance studies for EEHG operation at sFLASH were performed in 2011 [1] assuming a seed laser power of several gigawatts in the ultraviolet (UV). However, operation of a UV source with multi-GW peak power seems to be unfeasible. In the following, we will describe the challenges to operate EEHG at sFLASH and present a relaxed set of parameters for the first experimental tests.

EXPERIMENTAL SETUP

The Seeding Section in FLASH1

Figure 1 shows a schematic layout of the sFLASH installations. An overview of the entire FLASH facility can be found in [16]. After the energy collimator, the seeding section starts with two short electro-magnetic wigglers (labeled as MOD1 and MOD2) with 5 full periods [17] each followed by a magnetic chicane (labeled as 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 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. The following transverse deflecting structure (TDS) and a dispersive dump section allows to diagnose the longitudinal phase space distribution of the electron bunches. With that an accurate measure for the adjustment of laser-electron timing for both seed pulses is possible.

The Seed Laser

The 267-nm seed pulses are generated by third-harmonic generation (THG) of near-infrared (NIR) Ti:sapphire laser pulses. Two THG setups are fed by splitting the NIR pulses

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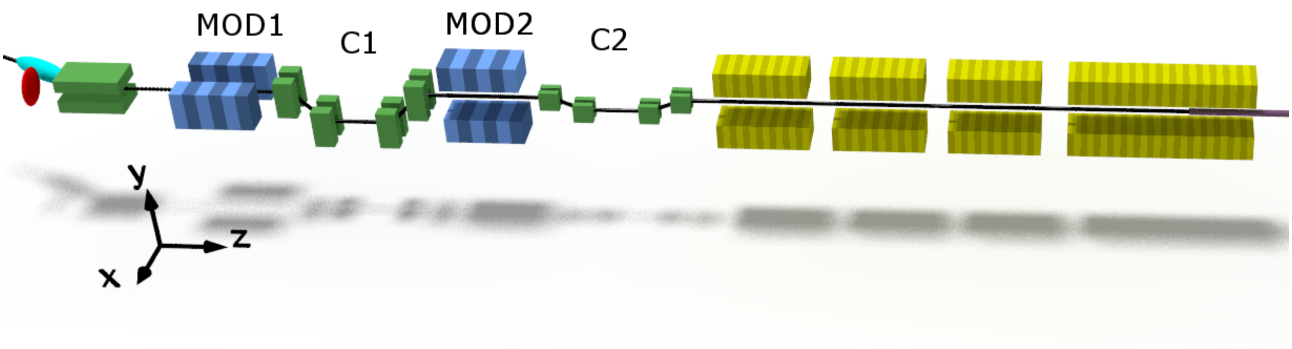

Figure 1: Layout of the FLASH1 beamline.

using a 50/50 beam splitter. For each UV beam, a maximum pulse energy of about 500 µJ is expected. Because there is no second injection port available, both UV beams are guided through the same seed injection system. A thin-film polarizer is used to combine both UV pulses at perpendicular polarization which is also necessary for MOD1 (vertical deflecting) and MOD2 (horizontal deflecting). The beam waist of the UV beams can be adjusted independently in MOD1 and MOD2.

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 [18]. 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 [19, 20]. 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 [21].

EEHG BUNCHING

The bunching factors for EEHG are given by [8]

$$b_h = \left| \sum_{m=-\infty}^{\infty} e^{im\phi} J_{-m-h} \{A_1[(m+h)B_1 + hB_2]\} J_m(hA_2B_2) e^{-(1/2)[(m+h)B_1+hB_2]^2} \right| \quad (1)$$

where h is the harmonic number, $A_j = \Delta E_j/\sigma_E$ are the normalized modulation amplitudes, and $B_j = R_{56,j} k\sigma_E/E_0$ ($j = 1, 2$) are the normalized dispersive strength of the two chicanes. Here, the energy modulation amplitudes ΔE_j, the rms slice energy spread σ_E, the electron beam energy E_0, the wavenumber $k = 2\pi/\lambda$ of the seed laser, and the longitudinal dispersions $R_{56,j}$ of the two chicanes are the experimental parameters. These parameters are compiled in Table 1.

Table 1: Experimental Parameters (for beam energies below 1 GeV, the longitudinal dispersion of chicane C1 is limited by the aperture of the vacuum chamber).

	parameter	**value**
modulator	period length	0.2 m
	effective length	1.2 m
	K (peak)	<10
radiator	period length	31.4 mm
	effective length	10 m
	K (peak)	<2.7
chicanes	R_{56} C1*	0-740 µm/GeV^2
	R_{56} C2	0-72 µm/GeV^2
	R_{56} C3	190 µm
electron beam	energy	0.7-1.2 GeV
	peak current	600 A
	charge	0.4 nC
	bunch duration	500 fs (fwhm)
seed beams	wavelength	267 nm
	pulse energy	<280 µJ
	pulse duration	250-280 fs (fwhm)
	Rayleigh length	1.6 m

The phase ϕ gives the relative phase between the footprint of the modulation density generated in the first modulator-chicane combination and the light field of the laser pulse in the second modulator. This phase term becomes negligible once the overshearing in the first chicane is large ($A_1B_1 \gg 1$). For the parameter range accessible with the hardware currently implemented at sFLASH, this is not the case. Therefore, the ϕ-dependency must be taken into account [1], since the adjustment of this phase term is beyond level of control. Figure 2 shows the average bunching $\langle b_{10}\rangle_\phi$ and the expected variations of bunching at the 10th harmonic $\sqrt{\mathrm{Var}_\phi(b_{10})}$ for $A_1 = A_2 = 5$, at a beam energy of $E_0 = 700$ MeV and an energy spread of $\sigma_E = 70$ keV. For the initial commissioning of EEHG at sFLASH such maps will be created for different harmonic orders, to identify a set

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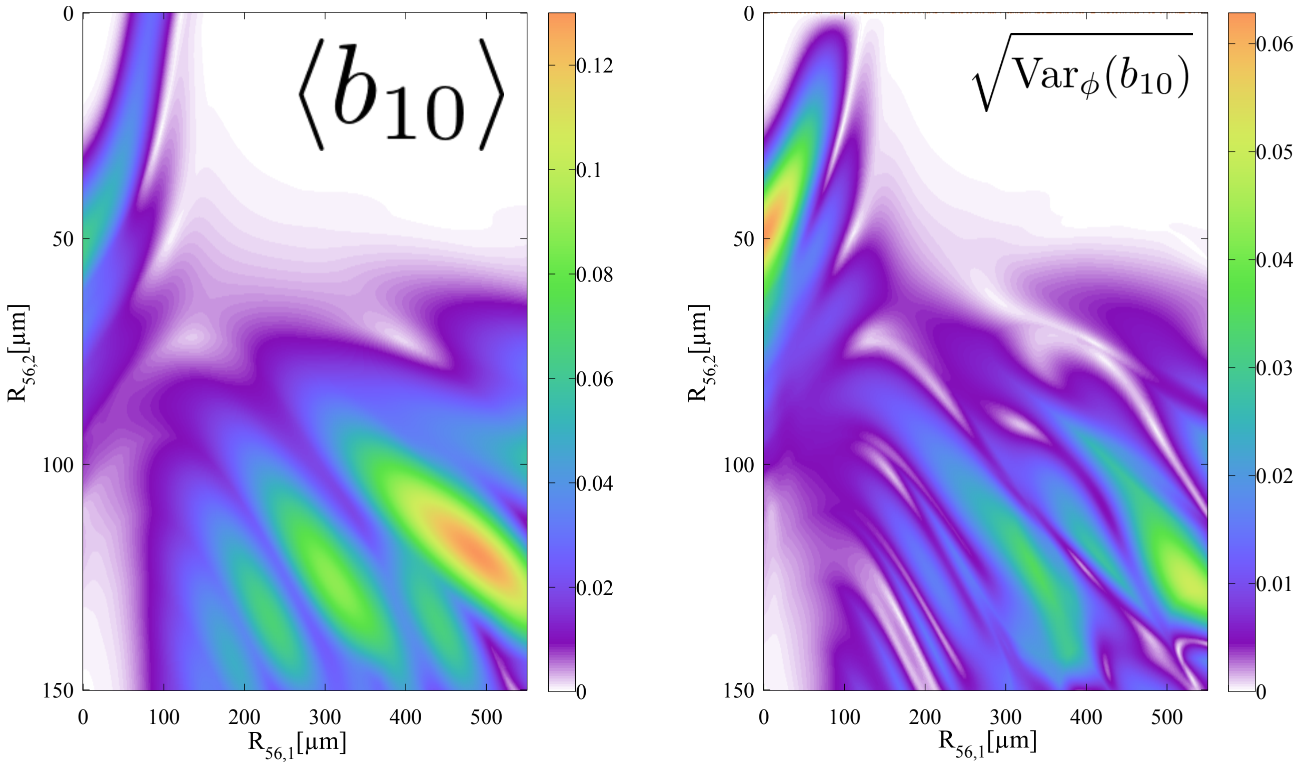

Figure 2: Bunching factor as a function of the longitudinal dispersions $R_{56,1}$ and $R_{56,2}$. The left panel shows the bunching factor $\langle b_{10} \rangle_\phi$ averaged over all phases ϕ. The right panel shows the standard deviation $\sqrt{\mathrm{Var}_\phi(b_{10})}$, indicating the fluctuations of b_{10} as the phase ϕ jitters. The choice of the operating point balances the average bunching $\langle b_{10} \rangle_\phi$ and the bunching jitter $\sqrt{\mathrm{Var}_\phi(b_{10})}$. Figure prepared for $A_1 = A_2 = 5$, $E_0 = 700$ MeV, and $\sigma_E = 70$ keV.

of R_{56} values which show a significant amount of average bunching, while the bunching fluctuations are low.

SUMMARY

In this contribution, we give a description of the EEHG setup at the experimental seeding setup at FLASH. From the experience of running the setup in HGHG mode [22], we decided to relax the operation parameters for the initial commissioning of EEHG and discuss the importance of the relative phase ϕ between the seed laser of the second modulator and the modulation feature imprinted by the first modulator-chicane combination. Based on previous work, we show how to find reasonable parameter sets which will allow to generate bunching in the XUV wavelength range.

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