OPTIMIZATION OF HHG SEEDING AT FLASH II

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Abstract

FLASH, the **F**ree-Electron **Las**er in **H**amburg, generates coherent XUV radiation used in various research projects. In order to provide more beam time for the growing community of photon users, DESY in collaboration with HZB started the FLASH II project. FLASH II is an extension of FLASH consisting of a new undulator section (See Fig. 1) in a separate tunnel and a new experimental hall. The two FEL share the same super conducting linac. Due to the fixed gap undulators used in the present FLASH setup the FEL-wavelength can be changed only by changing the electron energy. FLASH II, in contrast, will benefit from variable gap undulators which will allow to have largely independent radiation wavelength.

In the range of 10 nm to 40 nm a direct HHG seeding option is foreseen to improve the FEL radiation quality. For experiments it is important to have the saturation point of the FEL radiation at a constant longitudinal position, close to the end of the undulator. On the other hand, one would like to keep the waist of the HHG seed at a fixed longitudinal position, too, for all wavelengths. In this paper, we present an optimized configuration of the undulator gaps, assuming fixed positions for both, the HHG seed waist and the FEL radiation saturation point.

INTRODUCTION

The free-electron laser FLASH [1],[2] consists of a photocathode RF gun followed by a superconducting linac, which delivers a maximum electron energy of 1.25 GeV. The linac is followed by 27 m of fixed-gap undulators. The FEL operates in the SASE mode, producing FEL radiation with a wavelength down to 4.12 nm, corresponding to the maximum electron energy. Since FLASH can only deliver SASE radiation to a single experiment at a time, DESY and HZB proposed the FLASH II project - a second undulator branch driven by the same superconducting accelerator modules (see Fig. 1) [3].

The FLASH II project

For FLASH1 and FLASH2 (the two beamlines of the FLASH II facility) two different photocathode lasers will be used to produce two bunch trains within the same RF pulse, which consist of two temporally separated flat tops, one for each bunch train. Therefore the bunch trains will experience different acceleration gradients and phases allowing to independently tune the charge, beam energy and compression for each bunch train. A set of kicker magnets combined with a septum, downstream the last acceleration module, will extract one of the bunch trains to FLASH2 [4]. After a matching section the electrons enter the FLASH2 undulator beam line, consisting of 12 variable gap undulators installed in a FODO lattice. The current status of the project will be presented in [5], additional information can be found in [6].

Seeding option

For wavelength range between 10 nm and 40 nm a direct high-harmonic generation (HHG) seeding option is foreseen. A novel gas jet target has been developed for the seed source [7]. Alternatively, for the longer wavelengths, a target similar to the one of the sFLASH experiment (where seeding at 38.1 nm has already been demonstrated [8]) can be used. In order to reduce the overall number of mirrors and therefore the technical complexity of the HHG seed injection beam line, it is desirable to keep the seed waist position fixed. According to zemax calculations for the HHG setup at FLASH2, this point is inside the third undulator.

Photon user requirements

The photon users have to image the saturation point of the radiation to the respective target. The position of the saturation point depends among others on the FEL gain length and wavelength. The required effective undulator length increases with the decreasing wavelength. For SASE one can open undulators upstream such that the required saturation length is achieved. If the position of the source point (the onset of the FEL saturation) is kept at a fixed position, then from the users side focus adjustments will not be needed.

NUMERICAL SIMULATIONS

Goal

The goal of the numerical studies is to determine the optimal undulator configuration (gaps closed or opened), while keeping the HHG seed waist and FEL saturation point position fixed.

Undulator and simulation setup

The individual simulations were performed using the full 3D FEL simulation code `GENESIS 1.3` [9]. The FLASH2 undulator section consists of 12 variable gap undulators. The undulator parameters are given in Table 1. For seeding, only the undulator modules #3 through #12 are used. The position of the waist of the HHG beam is located inside undulator module #3. It is assumed that the gap of this undulator is always closed as the interaction of the seed and the electron beam takes place here. It has been also assumed that undulator gap #12 is always closed since the saturation

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ISBN 978-3-95450-123-6

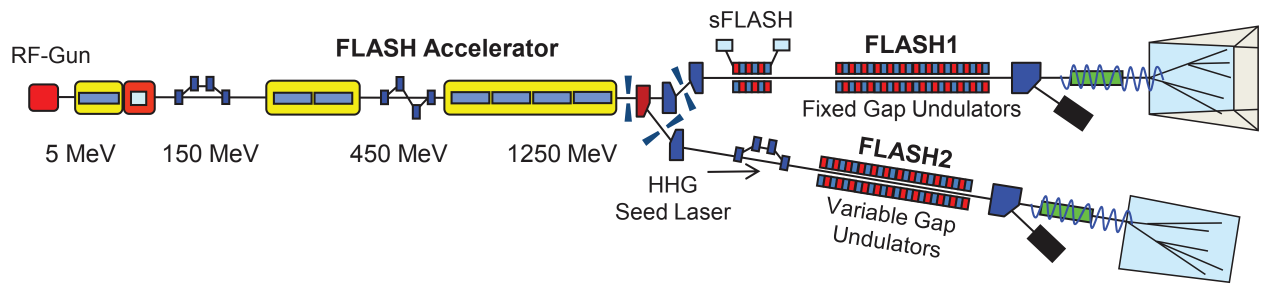


Figure 1: Schematic layout of FLASH with the FLASH II extension.

Table 1: Typical FLASH II parameter set used in the numerical simulations. For seeding only 10 undulators are considered.

Undulators		
Number of undulators		10 (of 12)
Undulator period	λ_{u}	31.4 mm
Undulator length	L_{u}	2.3864 m
Periods per undulator	N_{periods}	76
Undulator intersection	L_{drift}	87.92 cm
Max. K parameter (rms)	K_{rms}	2.0
HHG pulse		
Temporal shape		Gaussian
Wavelength	λ_{HHG}	37.6 nm
Pulse energy	E_{HHG}	70 pJ
Peak power	$P_{\mathrm{max,HHG}}$	2.5 kW
Duration (rms)	τ_{HHG}	12 fs
Rayleigh length	z_{ray}	2 m
Electron beam		
Peak current	I_{max}	2.5 kA
Bunch Length (rms)	σ_{e^-}	30 μm
Energy	E	700 MeV
Energy spread	σ_{E}	500 keV
Normalized emittance	$\epsilon_{\mathrm{x,n}}$	1.4 mm · mrad
	$\epsilon_{\mathrm{y,n}}$	1.4 mm · mrad

point should be located here. The gaps of the remaining eight undulators #4 through #11 can be opened or closed independently. Undulators with gaps opened are treated as drift spaces. All consecutive drift spaces are simulated as one long drift space. The gap of undulators #4 through #12 is assumed to be either opened or closed. Additional 2.5 m of virtual undulator length are simulated downstream to check for FEL saturation.

OPTIMIZATION OF UNDULATOR GAPS CONFIGURATION

For many wavelengths the total length of the undulators installed at the FLASH2 beam line will be considerably larger than the saturation length. In such cases some of the undulator gaps have to be open in order to reach saturation in the last undulator (i.e. to keep the saturation point fixed). Obviously, more than one possible undulator gap configurations are possible. In this contribution the optimization process for the undulator configuration will be shown using the initial conditions listed in table 1. With these initial conditions a number of time independent simulations have been performed in order to find a starting point for further optimization. The used figure of merit has been the peak power of the FEL radiation in the last undulator. The undulator configuration with the highest output power has been used in the next iteration of the optimization. After this time-independent run, a time-dependent simulation has been performed in order to check spectral properties of this undulator setting. As shown in Fig. 2 for the op-

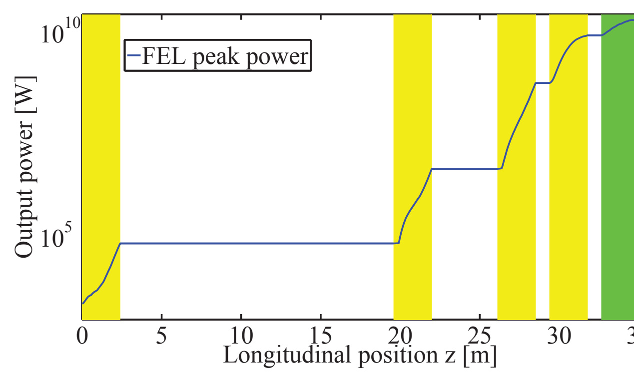
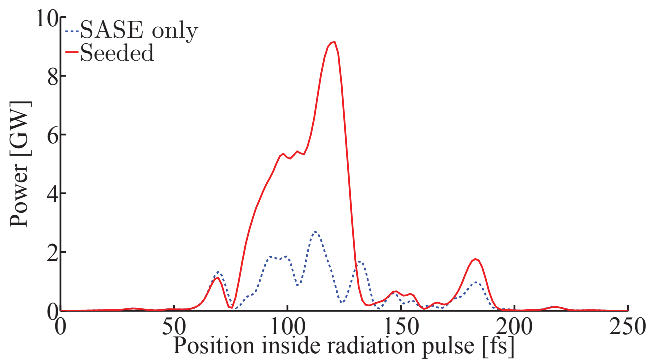


Figure 2: Best undulator gap configuration for a time-dependent simulation. Yellow bars mark closed undulators. The green bar is an additional undulator added for the simulation to check whether the FEL is in saturation or not. The blue line is the FEL peak power.

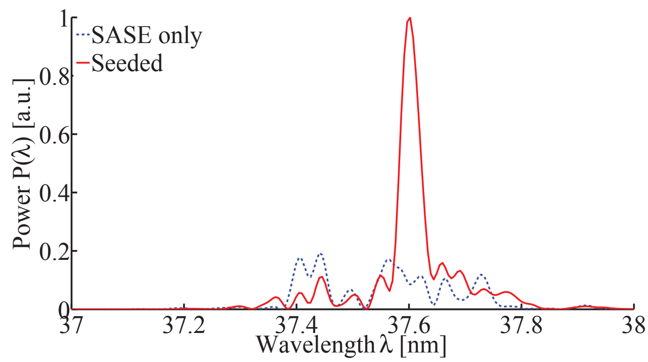
timal settings five consecutive undulator gaps have to be opened. This large drift space of about 17 m is introducing a slippage between electron bunch and FEL radiation. Due to the irregular arrangement of active undulators the slippage between radiation and electron motion introduces a complicated temporal profile of electron bunching and FEL radiation illustrated in Fig. 3(a). Inside undulator #9 the bunching introduced in undulator #3 will cause radiation while the radiation pulse from undulator #3, carrying a peak power of about 75 kW, will "seed" the bunch at a different longitudinal position. In undulator #11, after another

ISBN 978-3-95450-123-6

drift space, the first and second bunched regions inside the bunch start radiating. Due to the slippage inside the undulator, the first bunched region becomes wider. In undulator #12, both bunched regions radiate FEL pulses with a temporal difference. The undulator configuration is imprinted to the electron bunch in terms of bunching.



(a)

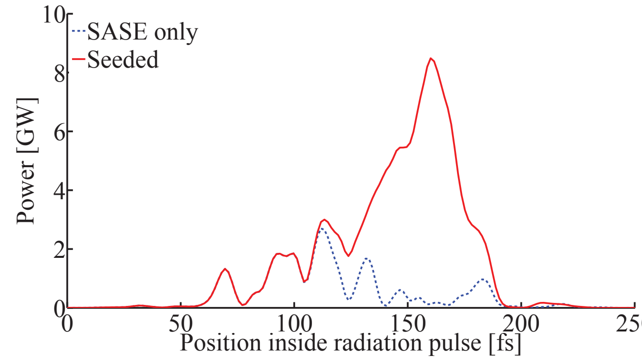


(b)

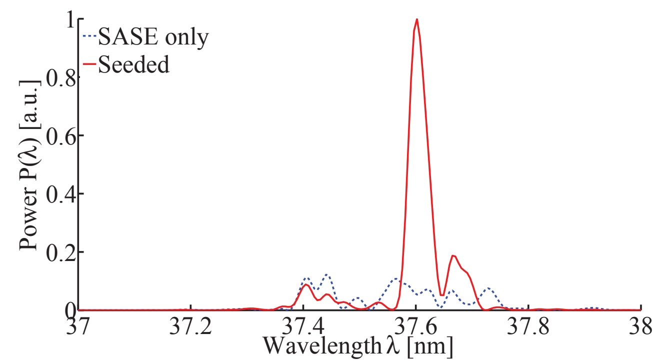
Figure 3: Longitudinal power distribution (a) and spectra (b) for a temporal offset of 54 fs, i.e. the electron bunch peak current arrives at the entrance of the first undulator 54 fs earlier than the HHG seed pulse. The head of the pulse is to the right. The radiation pulse yields an energy of 328 μJ.

Since the pre-pulse seen in Fig. 3(a) carries a significant amount of power, it could decrease the contrast and/or the temporal resolution of the user experiment. In order to study how to reduce the negative effect of this pre-pulse, several simulations were performed using different temporal offsets between the HHG seed and electron bunch. As shown in Fig. 4(a) the second pulse almost vanishes when the power peak of the seed pulse passes the first undulator entrance 7 fs prior to the current peak of electron bunch. In this case the seeded FEL pulse has an energy of about 395 μJ, while SASE contributes 114 μJ (see Fig. 5). However, one has to know that in the studies presented above a conservative estimation of the HHG seed pulse energy has been considered. As listed in Table 1 the assumed HHG pulse energy is about 70 pJ at the undulator entrance.

One can now look at the longitudinal position with the highest energy contrast. According to the power spectra



(a)



(b)

Figure 4: Longitudinal power distribution (a) and spectra (b) for a different offset. The peak power of the HHG seed radiation pulse arrives 7 fs earlier than the peak current of the electron beam (i.e. the seed pulse has been shifted by +68 fs with respect to Fig. 3. The head of the pulse is to the right. The radiation pulse yields an energy of 395 μJ.

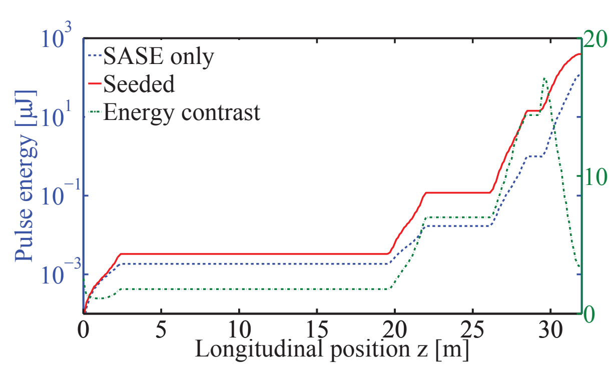
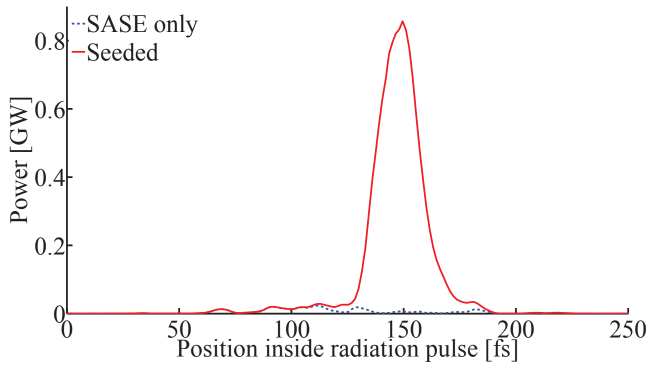


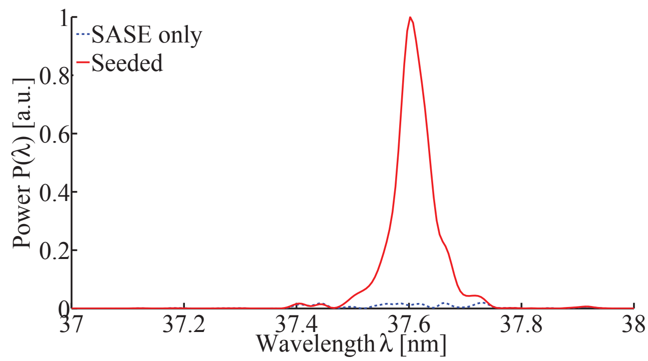
Figure 5: FEL pulse energies and energy contrast.

ISBN 978-3-95450-123-6

shown in Fig. 6(a) and the longitudinal power distribution shown in Fig. 6(b) the radiation pulse yields around 1.2 μJ SASE pulse energy (about 12 MW of power) and about 21 μJ (roughly 1 GW) in seeded operation. Since 70 pJ is a



(a)



(b)

Figure 6: Longitudinal power distribution (a) and spectra (b) at the position of the highest energy contrast (instead of the end of the last undulator as in Fig. 4) for the optimized temporal offset of 7 fs, optimized in terms of pre-pulse reduction. The head of the pulse is to the right. The radiation pulse yields an energy of 21 μJ.

conservative estimation, a number of simulations has been performed for HHG seed pulse energies in the range from 50 pJ to 10 nJ. The maximum energy contrast which can be expected from simulation can be seen in Fig. 7.

SUMMARY AND OUTLOOK

The direct HHG seeding option for FLASH II has been studied by the means of numerical simulations, assuming fixed positions for the HHG seed waist and the FEL saturation point. For a set of typical linac and HHG parameters an optimized undulator gap configuration has been found and investigated. The effect of the temporal offset between HHG seed and electron bunch on the longitudinal power distribution has been examined. However, optimization of this parameters leads to a longer FEL radiation pulse. It has been shown that at the position of the maximum energy contrast the radiation pulse is shorter but also less powerful and carrying less energy.

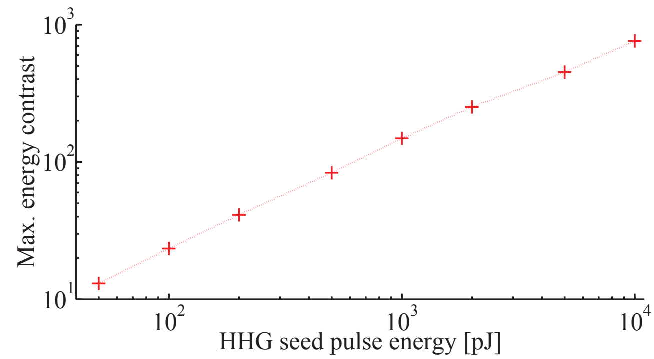


Figure 7: Maximum pulse energy contrast in dependence of the HHG seed pulse energy.

In the future several other wavelength and electron beam energies have to be studied in order to find the best solution for each of the possible operation parameters of FLASH II. Furthermore, tolerance studies have to be performed on the misalignment of quadrupole magnets as well as other beam line elements and linac parameters. It has to be investigated if different HHG seed pulse positions could increase the performance of the seeded FEL. In addition, a procedure to find the optimal setting in the erimental setup has to be developed and the agreement of the simulations and the experiment has to be investigated.

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