TOLERANCE STUDIES ON THE HIGH HARMONIC LASER SEEDING AT FLASH*

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Abstract

Currently the Free-electron-LASer at Hamburg (FLASH) operates in the Self-Amplified Spontaneous Emission (SASE) mode, delivering to users photon beams with wavelengths between 6.5 nm and 40 nm. In order to improve the temporal coherence of the generated radiation it is planned to externally seed FLASH with higher harmonics of an optical laser. The project aims for a seeding in the 30-13 nm range, with a stability suitable for user operation. In this contribution the performance of the seeded FEL is studied in simulations. An emphasis is placed on the tolerances of the most critical parameters such as electron beam transverse offset and angle with respect to the external seed, timing jitter and energy of the seed pulse.

INTRODUCTION

Currently FLASH operates in the SASE regime and produces EUV pulses of sub-10 fs duration [1]. Due to its start-up from noise, the SASE radiation consists of a number of uncorrelated modes resulting in reduced longitudinal coherence and shot-to-shot fluctuations (about 18 % rms [1]) of the output pulse energy. One possibility to decrease the magnitude of these fluctuations is, with the help of a 3.9 GHz RF cavity [2], to produce much longer (∼200 fs) radiation pulses, so that more modes contribute to the FEL output. However, in this case the increased EUV pulse

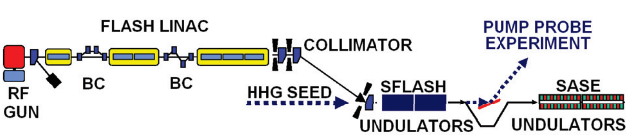

Figure 1: Schematic layout of the seeding experiment (not to scale), *BC* stands for bunch compressor stage.

length might not fit to the needs of ultrafast time resolved experiments. An alternative is to operate FLASH as an amplifier of an injected seed from a high harmonic generation (HHG) source. This approach gives several benefits compared to SASE. It makes possible to achieve higher shot-to-shot stability at GW-power level with a pulse duration given by the seed pulse of the order of 20 fs FWHM. The longitudinal coherence is expected to be greatly improved. The FEL output is synchronized with the external seed laser, thus enabling precise pump-probe experiments to be performed. As sketched in Fig.1, sFLASH will be installed at the end of the linac, upstream of the existing fixed-gap SASE-undulators. With the help of a dedicated optical beamline, the HHG seed will be inserted through the collimator section, making use of the electron beam offset of about 20 cm. After amplification in the sFLASH

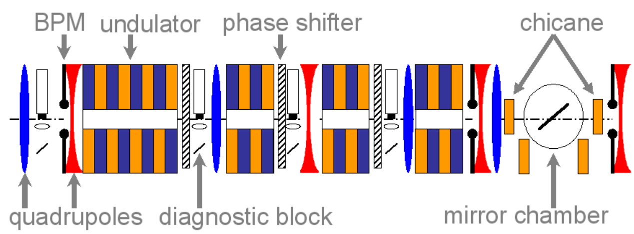

Figure 2: Schematic layout of the electron beamline in the seeding section.

variable-gap undulators, the output radiation is separated from the electrons by means of a mirror mounted in a small magnetic chicane downstream. The photons are then reflected towards the experimental area outside the FLASH tunnel. The layout of the electron beamline in the seeding section is illustrated in Fig.2. It consists of four planar variable-gap undulators of 10 m total length, separated by 70 cm intersections. The undulators, except the first one, are of the same type as those installed in the PETRA III synchrotron radiation source [3] with a period of 31.4 mm and a length of 2 m. The first undulator is a 4 m long PETRA II type [4] with 33 mm period. In order to extend the wavelength range, an undulator vacuum chamber with a vertical size of 9 mm will be installed.

TOLERANCE STUDIES

The aim for a stable seeded operation in the 30-13 nm range imposes certain requirements for the design of the experimental layout and for the electron beam parameters. It is mandatory to obtain a reproducible six-dimensional, $\{x, y, x', y', t, \lambda\}$, overlap between the seed and the electron bunch. Therefore, the beamline must include proper diagnostics and instrumentation to maintain the overlap within the desired tolerances, which according to the studies performed with GENESIS [5] , are of the order of

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$30\,\mu\mathrm{m}$ and $20\,\mu\mathrm{rad}$ in the transverse plane (see below). In order to minimize the impact of the timing jitter, the electron bunch length should be of the order of 260 fs rms, even though the state-of-the-art synchronisation system can restrict the jitter to less than 40 fs rms. Such operation mode can be realized only after the installation of the 3$^{\mathrm{rd}}$ harmonic (3.9 GHz) RF cavity. sFLASH has to run in parallel to and without disturbing the SASE operation. The SASE-undulators are fixed-gap devices and the SASE wavelength, given by the electron energy, is defined by the users. Therefore, for tuning the resonant wavelength of sFLASH one needs variable gap undulators. In the following the influence of key electron beam properties and beamline components, such as electron beam transverse offset and angle, energy in the resonant harmonic, temporal overlap, is considered. The performance of the seeded FEL has been studied with the 3-D time dependent FEL code GENESIS. The electron optics simulations have been performed with the code ELEGANT [6]

Transverse Offset of the Electron Beam

Whenever the electron bunch enters the undulator with an offset and(or) an angle it undergoes betatron oscillations as it propagates downstream. The excited coherent transverse motion disturbs the spatial overlap between the radiation field and the electron bunch. In addition it modulates the longitudinal velocity of the electrons and thus affects their ponderomotive phase with respect to the radiation field. These two effects, the so called beam wander

Table 1: Electron beam and seed parameters

Energy, E_0	850 MeV
Peak current, I_0	1500 A
rms bunch length, σ_z	80 μm
rms energy spread	0.2 MeV
Normalized rms emittance, ϵ_n	2 mm mrad
seed pulse duration, FWHM	20 fs
wavelength, λ_r	30 nm
energy in the harmonic	1 nJ

and phase shake, result in FEL performance degradation. As pointed out in [7] a transverse oscillation of amplitude larger than the electron beam size degrades the FEL performance mainly by the the phase shake effect, while the beam wander becomes dominant for smaller amplitudes. The impact of the electron beam misalignment on the performance of sFLASH has been studied with GENESIS in its steady state mode. The considered FEL parameters are summarized in Table1. Figure 4 shows the saturated power for an electron beam of different transverse offsets at the entrance of the sFLASH undulator. A radiation power tolerance of 5 % yields a maximal acceptable electron bunch offset on the order of $30\,\mu\mathrm{m}$ or about 30 % of the beam size ($100\,\mu\mathrm{m}$ rms).

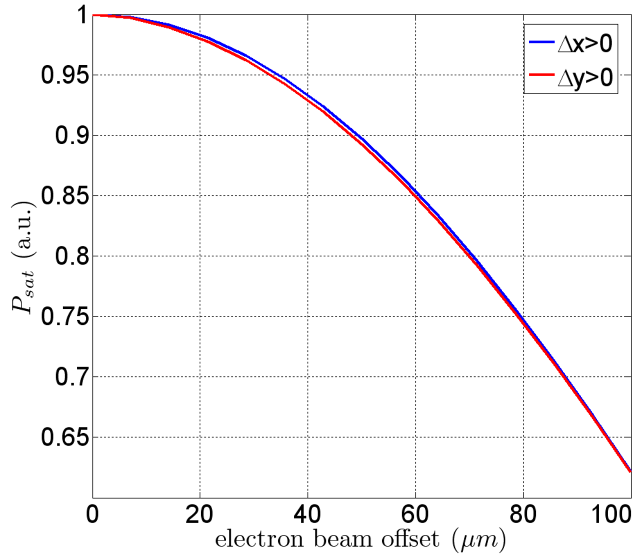

Figure 3: Radiation power vs. electron beam transverse offset Δx and Δy at the entrance of the sFLASH undulator.

Transverse Offset of the Seed Radiation

In the considerations so far it has been assumed the HHG seeding pulse is perfectly adjusted to the undulator axis. However the HHG source is located outside the FLASH tunnel and the HHG radiation is transported by means of movable mirrors mounted on translation stages in a dedicated beamline [8]. If the seed enters the undulator under

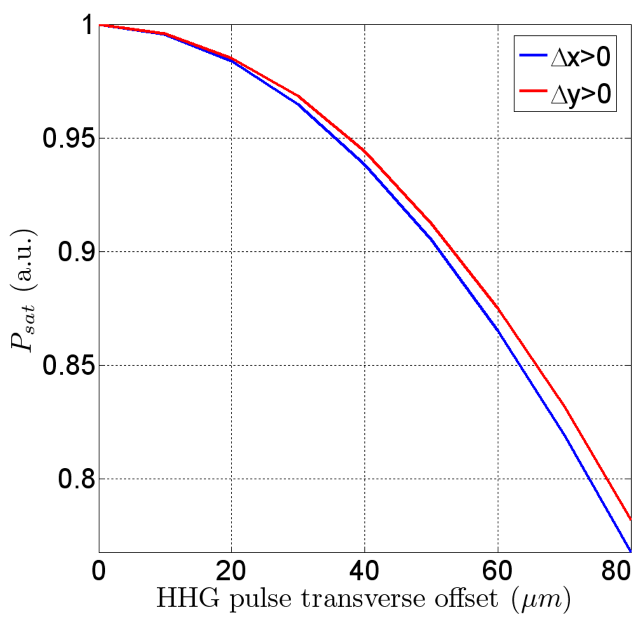

Figure 4: Radiation power vs. HHG seed transverse offset at the entrance of the sFLASH undulator.

an angle or with an offset this will disturb the overlap with the electron beam. Therefore the tolerances of the spatial and angular alignment of the HHG pulse have to be considered in the design of the beamline and the mirror motion

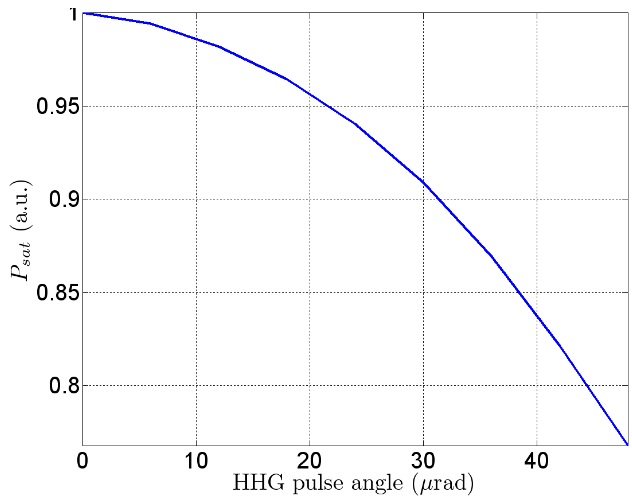

Figure 5: Radiation power vs. HHG seed angular offset at the entrance of the sFLASH undulator.

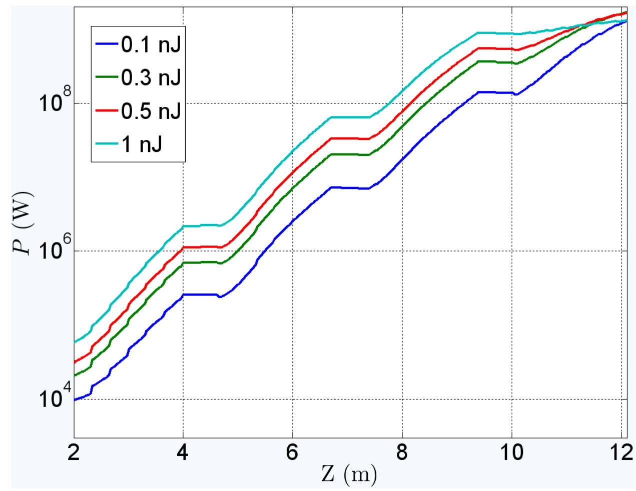

Figure 7: Radiation power in a seeded slice of the bunch at 30 nm along the sFLASH undulators.

control. This problem has been studied in simulations, assuming the same FEL parameters as listed in Table1. The simulation results, presented in Fig.4 and Fig.5, show the saturation power as a function of the initial transverse offset and angle of the HHG seed pulse. With these data and applying similar considerations as above, one can deduce the tolerances for the transverse offset (35 μm) and the angle (20 μrad) of the seed radiation.

Energy in the Seeding Pulse

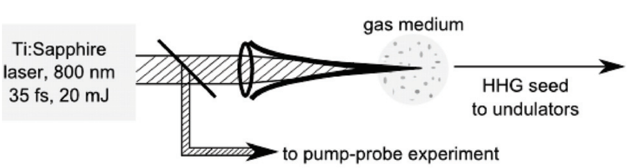

Figure 6: Schematic layout of the HHG source.

Figure 6 schematically shows the HHG source: Optical laser pulses (800 nm, 20 mJ, 35 fs) are split into two parts. The first part can be used for pump-probe experiments while the second part is focused onto a pulsed gas jet (argon) in order to create higher-order odd harmonics [10]. The harmonics are guided to the sFLASH undulator to seed the electron bunches. According to recent HHG experimental results scaled to a pump pulse energy of 14 mJ [9] one can expect the HHG pulse energy to exceed 100 nJ at 30 nm. Nevertheless the question of the lower seed power limit is of practical interest especially concerning the design of the HHG beamline and the future pump probe experiments. The graphs in Fig. 7 show the FEL power in the seeded part of the pulse along the sFLASH undulator. The time dependent GENESIS simulations have been performed for different HHG pulse energies from 0.1 nJ to 1 nJ. As visible, for 1 nJ energy in the resonant harmonic the onset of the nonlinear regime is reached after three undulator sections (or 8 m effective undulator length), while for the 0.1 nJ case the exponential growth regime extents over the full undulator length without reaching saturation. These simulation results are also in a good agreement with the values predicted by the Xie formulae [11]. Of great importance is also to assure a good contrast between the amplified pulse and the SASE radiation. Figure 8 shows a logarithmic plot of the radiation power for 1 nJ seed energy at saturation as a function of the local distance in the bunch. As visible the amplified seed (around s=75 μm) exceeds the SASE power by about three orders of magnitude. The signal-to-noise ratio $E_{seed}/E_{sase} \approx 80$, where $E_{seed} \approx 24\,\mu$J is the energy in the seeded part of the bunch and $E_{sase} \approx 0.3\,\mu$J is the total energy in the SASE pulse.

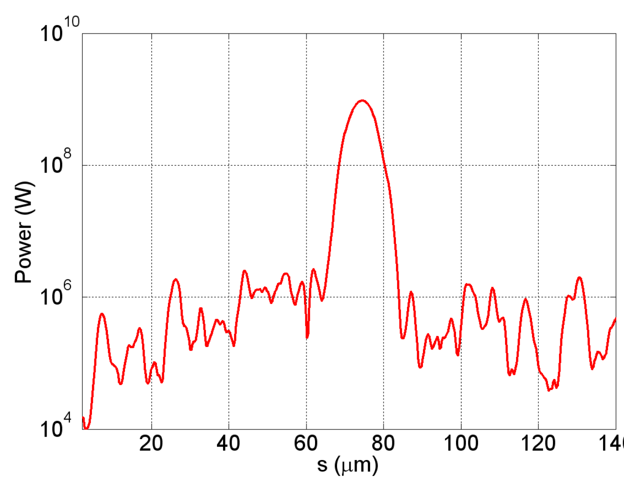

Figure 8: Radiation power at the onset of the nonlinear regime (see Fig.7) as a function of the local distance in the bunch. The energy in the seeding harmonic is 1 nJ.

Timing Jitter

Mandatory for a stable seed operation is an excellent timing overlap between the electron bunches and the HHG pulses. To minimize the timing jitter the electron bunch arrival time has to be actively stabilized using an intra-pulse train feedback [12] regulating the gradient of the accelerating modules prior to the first bunch compressor stage. For

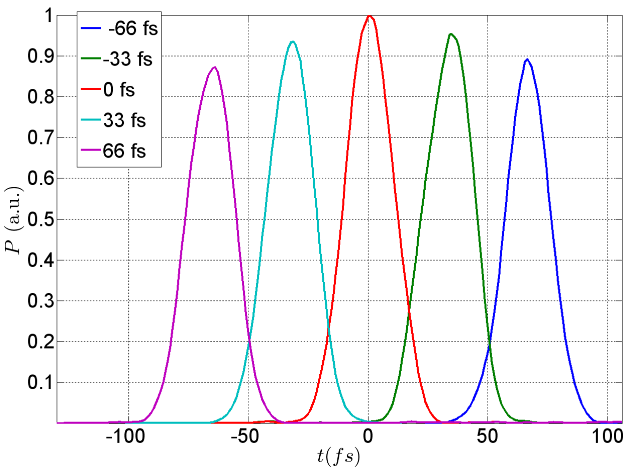

Figure 9: Longitudinal profiles of the FEL pulse at the onset of the nonlinear regime with different temporal offsets applyed to the seed.

the feedback, the electron bunch arrival time is detected by sampling a fast transient signal from a broadband pickup using laser pulses from a femtosecond stable optical synchronization system [13]. The seed laser system is locked with femtosecond precision to the optical synchronization system using a two-color balanced optical cross-correlator currently under development [14]. The influence of the timing jitter on the sFLASH output power has been investigated applying diffrent temporal offsets ($\pm$ 66 fs, $\pm$ 33 fs) to the simulated seed pulse. A summary of the obtained results is plotted in Fig 9. The graphs in the figure show the temporal profile of the FEL pulse as a function of the local distance in the bunch. The considered electron bunch length of 630 fs FWHM (see Table 1) is about an order of magnitude larger than the maximal time offset. This mitigates the effect of the disturbed longitudinal overlap between the electron bunch and the HHG radiation to about 5 % FEL power reduction for the 30 fs offset.

SUMMARY

The stability requirements of the HHG seeding experiment has been studied in simulations. Condideration was given to the tolerances needed to achieve spatial, angular and temporal overlap between the HHG seed and the electron bunch. The impact of the energy in the HHG harmonic has been discussed and the expected properties of the FEL radiation have been analysed.

REFERENCES

[1] W. Ackermann et. al. Nature Photonics 1, 336 - 342 (2007)

[2] K. Flöttmann et al., "Generation of Ultrashort Electron. Bunches by cancellation of non-linear distortions in the longitudinal phase space", TESLA-FEL-2001-06

[3] M. Tischer et. al., "Insertion Devices for the PETRA III Storage Ring", SRI'06, Daegu, May 2006, pp. 343-346

[4] K. Balewski et. al., "An Undulator at PETRA II - A New Synchrotron Radiation Source at DESY", Proceedings of the 16th International Conference on High Energy Accelerators, Dallas, Texas, USA, 1, 275 (1995)

[5] S. Reiche, Nucl. Instr. and Meth. A 429, 243 (1999)

[6] M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," Advanced Photon Source LS-287, September 2000.

[7] S. Reiche, Nucl. Instr. and Meth. A 445 (2000) 139

[8] S. Khan et. al. "sFLASH: AN EXPERIMENT FOR SEEDING VUV RADIATION AT FLASH", these proceedings

[9] B. McNeil et.al., New Journal of Physics 9 (2007) 82

[10] Carsten Winterfeldt et.al., Rev. Mod. Phys. 80, 117 (2008)

[11] M. Xie, NIM A445 (2000) 59-66

[12] F. Loehl et. al., "Observation of 40 fs Synchronization of Electron Bunches for FELs", these proceedings

[13] XFEL Technical Design Report 2006, DESY-2006-097

[14] Sebastian Schulz et.al., "An Optical Cross-correlation Scheme to Synchronize Distributed Laser Systems at FLASH", Proceedings of EPAC 2008, Genua, Italy