

AN OPTION TO GENERATE SEEDED FEL RADIATION FOR FLASH1*

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Abstract

The FLASH free-electron laser (FEL) at DESY is currently operated in self-amplified spontaneous emission (SASE) mode in both beamlines FLASH1 and FLASH2. Seeding offers unique properties for the FEL pulse, such as full coherence, spectral and temporal stability. In this contribution, possible ways to carry the seeded FEL radiation to the user hall are presented with analytical considerations and simulations. For this, components of the sFLASH seeding experiment are used.

INTRODUCTION

FLASH is the soft X-ray free-electron laser (FEL) user facility operated at DESY in Hamburg [1, 2]. The electron bunches produced from the photo-injector of FLASH are accelerated and delivered to three different beamlines: FLASH1, FLASH2 and the recently commissioned new beamline FLASH3 with the FLASHForward [3] experiment, dedicated to studies on beam-driven plasma wakefield acceleration. During user operation, FLASH1 and FLASH2 deliver self-amplified spontaneous emission (SASE) FEL radiation to the experimental halls. The unique properties of the FLASH photo-injector and the superconducting RF accelerating structures permit up to 800 bunches per RF pulse [4]. Nevertheless, the properties of the FEL pulses can be further improved with innovative seeding techniques. The main advantages of a seeded FEL are the high spectral and power stability and the longitudinal coherence. These improved properties arise from starting up the FEL process from the microbunching developed from the interaction with a coherent seed pulse. Installed upstream of the main undulator of FLASH1, the sFLASH experiment is dedicated to studies of FEL seeding [5]. During dedicated sFLASH beamtime, only one electron bunch per RF pulse is generated by the photo-injector, resulting in a repetition rate of 10 Hz. So far the sFLASH beamline has been operated in the high-gain harmonic generation scheme (HG HG) [6], which provides seeded FEL radiation at the 7th and 8th harmonics of the seed. Currently, echo-enabled harmonic generation (EEHG) is under study [5]. The photon pulses produced by the sFLASH experiment are extracted from the electron beamline in an extraction chicane placed in front of the FLASH1 main undulator. As the sFLASH beamline offers a seed laser system, it is interesting to theoretically study the

possibility of producing HG HG-seeded FEL radiation and delivering it to the FLASH1 experimental hall.

SELECTED BEAMLINE ELEMENTS FOR SEEDING FLASH1

Figure 1 shows a schematic representation of the essential elements that are already present at FLASH and would be used for the HG HG operation. The scheme uses the second modulator of the sFLASH section, where the electron bunch is energy modulated by interacting with the seed laser pulse. The extraction chicane after the sFLASH radiator converts the energy modulation into a density modulation and the main undulator of FLASH1 is used as radiator. The FLASH1 undulator has a fixed gap, so one has to tune very carefully the energy of the electron beam in order to satisfy the FEL resonance condition at the desired wavelength, as detailed in the following section.

ANALYTICAL CONSIDERATIONS

Achievable Energy Modulation

The Ming Xie formalism [7, 8] has been used to estimate the maximum achievable power for the seeded FEL and its gain length.

The energy modulation amplitude of the electron beam resulting from the interaction with the seed laser pulse in the modulator is given by [9]

$$\Delta\gamma = \sqrt{\frac{P_L}{P_0} \frac{2K_{\text{MOD}} \cdot JJ \cdot L_{\text{MOD}}}{\gamma w_0}}, \quad (1)$$

where P_L is the laser pulse power, which is set to 100 MW in our calculations, w_0 is the seed laser pulse waist, $P_0 = I_A m_e c^2 / e \approx 8.7$ GW, where $I_A = m_e c^3 / e \approx 17$ kA is the Alfvén current, γ is the electron beam Lorentz factor, L_{MOD} is the overall length of the modulator and K_{MOD} is the undulator parameter (K) of the modulator, which has a maximum value of 10.8 and is adjusted in order to match the resonance condition $\lambda_l = \lambda_{\text{MOD}} \cdot (1 + K_{\text{MOD}}^2 / 2) / (2\gamma^2)$, in our case $\lambda_l = 266$ nm. Furthermore, $JJ = J_0(K^2 / (4 + 2K^2)) - J_1(K^2 / (4 + 2K^2))$ is a correction of the coupling between the fundamental light wave and the electron bunch in the planar undulator (J_n is the Bessel function of the first kind of order n), and $\lambda_{\text{MOD}} = 0.2$ m is the period length of the modulator. $\Delta\gamma$ has been calculated for beam energies between 450 and 700 MeV. Even if Eq. 1 is an approximation, because the impact of both the transverse and the longitudinal intensity distribution of the seed laser pulse is not taken into account, the estimated energy modulation $\Delta\gamma m_e c^2$ is comparable to

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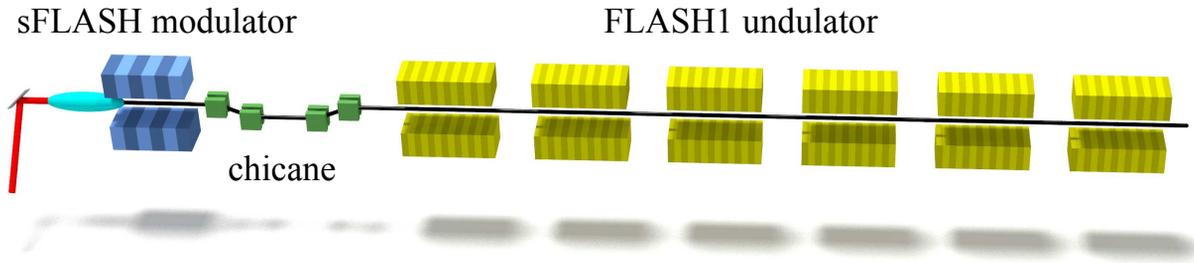


Figure 1: Essential components required for the proposed operating scheme. The red line indicates the path of the seed laser pulses.

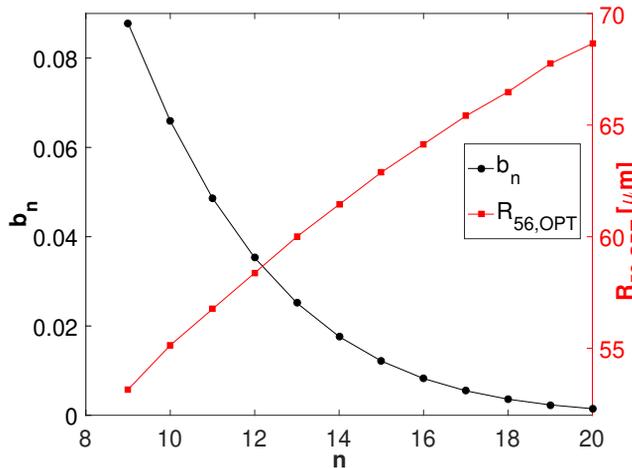


Figure 2: The plot shows the maximum bunching factor b_n for the different harmonics on the left axis and the R_{56} values on the right axis that gave these b_n .

the value measured during the normal sFLASH operation: $\Delta\gamma mc^2 \approx 404$ keV [10].

Possible Achievable Harmonics

As the FLASH1 main undulator has a fixed gap, corresponding to an undulator strength of $K_{\text{RAD}} = 1.23$, there are only a few harmonics of the seed that are allowed. The resonance condition

$$\lambda_{\text{FEL}} = \lambda_{\text{RAD}} \frac{1 + K_{\text{RAD}}^2/2}{2\gamma^2} \quad (2)$$

allows operation ranging from the 9th to the 20th harmonic for electron beam energies between 450 and 700 MeV.

Estimation of the FEL Performance

With the modified Ming Xie formalism we can estimate the saturation power for the HGHG-seeded FEL [7]:

$$P(z) = P_{\text{th}} \left[\frac{\frac{1}{3} \left(\frac{z}{L_g}\right)^2}{1 + \frac{1}{3} \left(\frac{z}{L_g}\right)^2} + \frac{\frac{1}{2} \exp\left[\frac{z}{L_g} - \sqrt{3}\right]}{1 + \frac{P_{\text{th}}}{2P_{\text{F}}} \exp\left[\frac{z}{L_g} - \sqrt{3}\right]} \right], \quad (3)$$

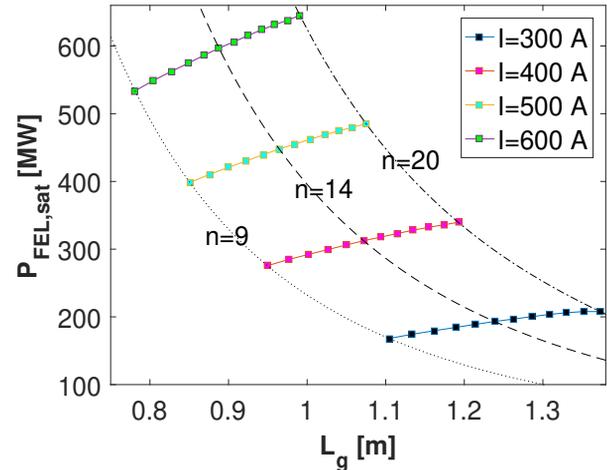


Figure 3: Saturation power and gain length for the harmonics in the accessible range and for several peak currents. Black curves indicate the saturation power for $n = 9, 14$ and 20 .

where z is the coordinate along the radiator that has an overall length of $L_{\text{RAD}} = 27$ m and is normalized with L_g , which is the power gain length. $P_{\text{th}} = \rho_{\text{FEL}} |b_n|^2 P_{\text{beam}}$ is the power at the transition from the regime of quadratic increase (coherent harmonic generation) to the onset of the exponential growth of the FEL power, ρ_{FEL} is the Pierce parameter, b_n is the bunching factor at the n th harmonic of the seed wavelength, $P_{\text{beam}} = \gamma mc^2 I_{\text{peak}}/e$ is the power of the electron beam and $P_{\text{F}}^* = P_{\text{F}} - P_{\text{th}}$, where P_{F} is the saturation power obtained from the correction given by Ming Xie [8].

The bunching factor for the different harmonics n [6] is

$$b_n = \exp\left(-\frac{1}{2} B^2 n^2\right) J_n(-nAB), \quad (4)$$

where $A = \Delta\gamma/\sigma_\gamma$ is the energy modulation $\Delta\gamma$ imprinted by the seed laser pulse on the electron beam normalized to the intrinsic energy spread of the electron bunch σ_γ . $B = R_{56} k_1 \sigma_\gamma/\gamma$, where R_{56} is the longitudinal dispersion from the modulator to the radiator. For each harmonic, we have optimized the bunching factor by adjusting the R_{56} value. Figure 2 shows the achievable bunching factor for each harmonic number at which the FEL radiation is pro-

duced. The right vertical axis indicates the corresponding optimal values for R_{56} .

Figure 3 shows the calculated saturation power and the gain length at different currents (300 A, 400 A, 500 A, and 600 A) for the allowed harmonics. In all the cases, saturation is reached significantly before the end of the radiator. In addition, the figure suggests that going for higher harmonics would be more advantageous because saturation is reached later in the radiator and the saturation power is higher. Operation at high peak currents makes it more difficult to differentiate the seeded FEL power signal from the SASE signal. Table 1 shows an estimation of the contrast between the SASE and seeded signal for the different currents for the simulations that are presented in the following section.

WORKING POINT SIMULATION

Simulations with the FEL code GENESIS1.3 [11] have been run to study the resulting photon pulses for different electron beam peak currents (300 A, 400 A and 500 A) at the 14th harmonic. An emittance of 1mm-mrad and an intrinsic energy spread of $\sigma_\epsilon = \sigma_\gamma mc^2 = 60$ keV has been assumed for the electron beam. In addition, the energy of the electron bunch has been set to $E = 576$ MeV to meet the resonance condition in the fixed-gap radiator. For the purpose of this simulation, the electron beam transport from the modulator to the radiator (including the chicane) was modeled by a transfer matrix.

Figure 4 shows the FEL pulses at different positions along the radiator for the different currents. We observe that the contrast between SASE radiation and seeded FEL radiation is not satisfactory at the end of the radiator, but it is still acceptable after the fourth undulator. The FEL pulse energies at the end of the fourth undulator obtained in the simulation are compiled in the Table 1. The last column of the table

shows the contrast between the energy of the seeded FEL pulse and the SASE one. A set of simulation with seed laser pulse off has been performed to get the energy of the SASE FEL pulse ($\text{energy}_{\text{SASE}}$). As FLASH1 has quadrupoles installed on movers after each undulator module, it is possible to stop the FEL amplification process by kicking the electron bunch. In fact a quadrupole displaced transversely with respect to the beam direction acts as a dipole on the electron beam. To kick the electron beam, preventing it to enter into the next undulator, the mover is set to the maximum displacement 0.95 mm.

Table 1: FEL pulse energies obtained from GENESIS simulations for the 14th harmonic.

current	energy	peak power	$\frac{\text{energy}_{\text{seeded}}}{\text{energy}_{\text{SASE}}}$
300 A	6.8 μJ	149.7 MW	20
400 A	12.3 μJ	320.3 MW	5
500 A	15.7 μJ	514.3 MW	2

CONCLUSION

In this contribution, theoretical studies of HGHG-seeded operation of FLASH1 using the already existing infrastructure have been presented. Analytical calculations and simulations are in good agreement. The FEL process in the seeded fraction of the electron bunch is saturated after four (out of six) undulator modules. To preserve the energy contrast between seeded and SASE FEL pulses the FEL process can be stopped by kicking the electron beam using a quadrupole magnet. By doing so, a seeded FEL pulse with an energy of the order of 10 μJ is obtained.

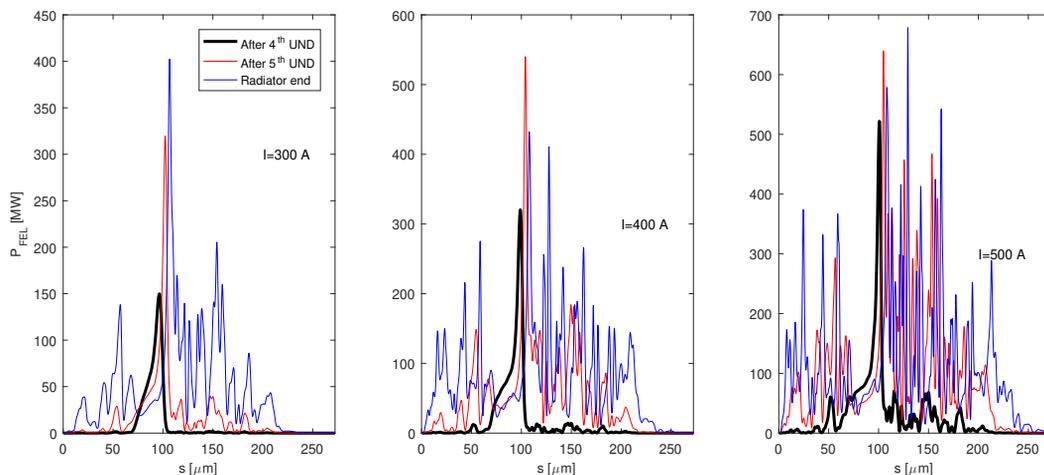


Figure 4: The FEL pulse power profile P_{FEL} is shown as a function of the longitudinal coordinate of the electron bunch s for different electron beam peak currents, from left to right: 300 A, 400 A and 500 A. Each plot shows the FEL pulse at different positions inside the radiator: after four undulators (black), after five undulators (red) and at the very end of the radiator (blue).

REFERENCES

- [1] W. Ackermann *et al.* “Operation of a free-electron laser from the extreme ultraviolet to the water window”, *Nat. Photon.*, vol. 1, p. 336, 2007.
- [2] M. Vogt *et al.*, “Status of the Superconducting soft X-Rays Free-Electron Laser FLASH at DESY”, presented at IPAC’18, Vancouver, Canada, May 2018, paper TUPMF089.
- [3] V. Libov, “FLASHForward Electron Beamline Commissioning”, presented at IPAC’18, Vancouver, Canada, May 2018, paper TUPML037.
- [4] T. Plath *et al.* “Free-electron laser multiplex driven by a superconducting linear accelerator”, *J. Synchrotron Rad.*, vol. 23, p. 1070, 2016.
- [5] C. Lechner *et al.*, “Status of the sFLASH Experiment”, presented at IPAC’18, Vancouver, Canada, May 2018, paper TUPMF085.
- [6] L. H. Yu, “Generation of Intense UV Radiation by Subharmonically Seeded Single-Pass Free-Electron Lasers”, *Phys. Rev. A*, vol. 44, p. 5178, 1991.
- [7] L. Giannessi, “Seeding and Harmonic Generation in Free-Electron Lasers” in E. J. Jaeschke *et al.* (Eds.) “Synchrotron light Sources and Free-Electron Lasers: Accelerator Physics, instrumentation and Science Applications”, Springer, pp. 195-223, Jan 2016, doi : 10.1007/978-3-319-14394-1_3
- [8] M. Xie “Exact and Variational Solutions of 3D eigenmodes in high-gain FELs”, *Nucl. Instrum. and Meth. A*, vol. 445, p. 59, 2000.
- [9] E. Hemsing *et al.*, “Beam by design: Laser manipulation of electrons in modern accelerators”, *Rev. Mod. Phys.*, vol. 86, p. 897, 2014.
- [10] T. Plath, “Measurements and Detailed Analysis of Seeded High-Gain Free-Electron Lasers at FLASH”, dissertation, University of Hamburg, Germany, 2017.
- [11] S. Reiche, “GENESIS 1.3: a fully 3D Time-Dependent FEL Simulation Code”, *Nucl. Instrum. and Methods Phys. Res. A*, vol. 429, p. 243, 1999.