# SIMULATION STUDIES FOR A EEHG SEEDED FEL IN THE XUV *

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## Abstract

Echo-enabled harmonic generation (EEHG) is a promising technique for seeded free electron lasers (FELs) not only to go down to wavelengths of 4 nm but also to simplify the schemes that are currently used to achieve a similar wavelength range (double cascade HGHG). Thus a study optimizing the EEHG performance in the wavelength range from 60 to 4 nm has been performed. The more critical working point, at 4 nm, is here analyzed in terms of seed laser stability for two different seed laser frequencies: visible and UV.
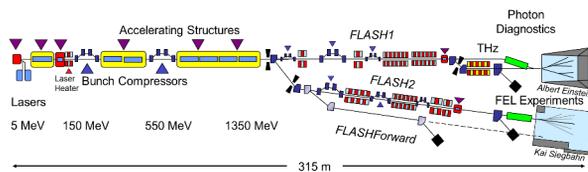
Figure 1: Layout for the FLASH 2020+ upgrade.

## INTRODUCTION

FLASH is the free-electron laser in DESY, Hamburg [1]. It is in operation since 2005, delivering self-amplified spontaneous emission (SASE) radiation down to 4 nm to user-experiments. FLASH has three beamlines: FLASH1, FLASH2 and FLASHForward. Simultaneous operation between FLASH1 and either FLASH2 or FLASHForward is possible [2]. In addition, the sFLASH (seeding at FLASH) experiment [3], is installed upstream of the fixed gap undulator in FLASH1.

In this paper we will focus on the seeding upgrade of the FLASH1 beamline presented in [4], in this frame both HGHG and EEHG schemes are foreseen. Therefore to design the beamline is necessary to estimate the effects induced by collective effects on the electron beam, like ISR and CSR, and limitations driven by energy chirps. On the other hand the decision on the seed laser to use will require studies on: laser stability, maximum power available, damage threshold for the optics and beam quality. In this paper we are going to study the performance of the FEL depending on the stability of the seed laser power for the generation of 4 nm. Further studies are necessary for the other important aspects regarding the seed laser and the electron beam.

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The considerations presented in this paper are based on the framework of the DESY2030 strategy program In particular the upgrade to seeding for the FLASH1 beamline.

## FLASH2020+ UPGRADE

Figure 1 shows the layout for the planned upgrade for FLASH. It includes the installation of a laser heater, an energy upgrade and new undulators in FLASH2 for more advanced FEL concepts [5, 6].

On the other side, FLASH1 will be operated in seeding mode with wavelength range between 60 and 4 nm. The present fixed gap undulators will be replaced by variable gap helical undulators. For seeding, two planar undulators, each followed by a magnetic chicane composed by four dipoles, will be installed before the radiator section. The first chicane having significantly higher longitudinal dispersion compared to the second for the echo-enabled harmonic generation scheme (EEHG).

In order to achieve the wavelength range required by the photon science community, two working points with different electron beam energy are proposed: 0.75 GeV and 1.35 GeV. The HGHG scheme will be used to generate wavelengths between 60 nm and 30 nm and the EEHG for wavelengths from 30 nm to 4 nm.

The final decision on the seed laser wavelength to use for the seeding is still pending, the candidates are in the ultra-violet (uv), tunable in the range 294 and 327 nm, and in the visible (vis), tunable in the range 413 and 480 nm. In this paper we compare the performance of both cases at the most demanding wavelength of 4 nm.

## SEEDING SCHEMES AND MOTIVATION

In this section we are going to give a fast overview on the seeding techniques considered for FLASH upgrade: HGHG and EEHG. We present the proposal to use these different seeding schemes to achieve different seed laser wavelengths with considerations on the bunching factor. The bunching factor $b$ characterizes the FEL power $P_{FEL} \approx |b|^2$.

### EEHG and HGHG Mechanism

The HGHG scheme needs only one modulator-chicane section and is well described in the paper [8]. We just recall here the bunching factor formula:

$$b_{a_H} = \exp\left(-\frac{1}{2}B^2 a_H^2\right) J_{a_H}(-ABa_H) \qquad (1)$$

where $a_H$ is the target harmonic of the seed laser, $A = \Delta E/\sigma_E$ is the the fraction between the energy modulation received by the electron beam through interaction with the seed laser in the modulator $\Delta E$ and the uncorrelated energy spread of the electron beam $\sigma_E$. B is proportional to the chicane dispersion $R_{56}$ and inversely proportional to the electron beam energy $E_0$ $B = R_{56}k\sigma_E/E_0$ .

On the other side the EEHG scheme needs one additional combination of modulator and chicane upstream to the radiator. A complete description of this scheme could be found in [7]. The EEHG bunching factor at a certain harmonic $a_E = n + m$ assuming the same seed laser wavelength in both modulators, is described by:

$$b_{n,m} = | \exp\left(-[nB_1 + a_E B_2]^2/2\right) J_n(-A_1[nB_1 + a_E B_2]) \\ J_m(-a_E A_2 B_2) |$$

where $A_{1,2}$ and $B_{1,2}$ are defined respectively as the A and B parameter in the HGHG model. For A the indices 1 and 2 refer respectively to the modulation received in the first and in the second modulator, while for B they represent dispersion in first and second chicane.
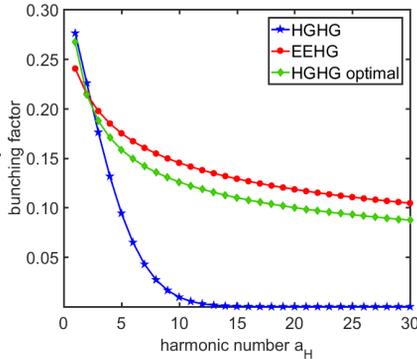


Figure 2: Bunching factor as a function of the harmonic number. The red dots represent the maximum of EEHG bunching factor for the considered working point (Tab. 1). The blue dots are the HGHG bunching factor calculated using the optimal parameters ($A_2$ and $B_2$) for the EEHG. Finally the yellow dots represent the HGHG bunching with optimized parameters.

In Fig. 2 the bunching for HGHG (yellow dots) is compared to the EEHG bunching (red dots) at harmonics of the seed laser up to the 30th. In the same plot the blue dots represent the HGHG bunching factor calculated using the parameters maximizing the EEHG bunching: $A_2$ and $B_2$. The HGHG bunching remains quite important up to the tenth harmonic, therefore if we would use EEHG also at low harmonics we would have to develop a technique to suppress the HGHG signal. Then, at low harmonics we just take advantage of HGHG. At high harmonics HGHG bunching factor is well approximated by $b_n \approx n^{-1/3}$. In order to get rid of the exponential suppression we would need to set $A \approx n$ and

$B \approx n^{-1}$. Meaning, an energy modulation $\Delta E = n\sigma_E$. Satisfying this condition at harmonics higher then the tenth is challenging for the FEL performance because a too high energy spread of the electron beam suppresses the FEL lasing. Luckily the EEHG scheme allows to get significant bunching at high harmonics with moderate energy modulation of the electron beam ($A_1$ and $A_2$). Thus the EEHG scheme will be exploited to produce wavelengths from 30 to 4 nm.

In Table 1 there are the electron beam and seed laser parameters used for the simulations.

Table 1: Table with the Main Electron Beam Parameters and the Seed Laser Wavelengths Used for the Two Cases (uv and vis)

| $E_0$[GeV] | $\sigma_E$[keV] | $A_1$ | $A_2$ | $\lambda_{UV}$[nm] | $\lambda_{VIS}$[nm] |
|---|---|---|---|---|---|
| 1.35 | 150.2 | 3 | 5 | 300 | 420 |

## SEED LASER TOLERANCES

The EEHG bunching factor is sensitive to seed laser modulations, in particular at very high harmonics. From tolerance studies in [9], one concludes that high harmonics are especially sensitive on the $A_2$ parameter. The formula that is explaining this variation is the following:

$$\frac{\Delta b_{n,m}}{b_{n,m}} = -\frac{(\Delta A_2)^2}{2A_2^2}[(j'_{m,1})^2 - m^2] \qquad (2)$$

$\Delta b_{n,m} = \tilde{b}_{n,m} - b_{n,m}$ is the difference between the bunching factor at the working point for the chosen $A_2$: $b_{n,m}$, and the bunching at the effective $A_2$: $\tilde{b}_{n,m}$.

The variation of the bunching relative to variation of the first seed laser modulation does not depend on the harmonic number if we work at a fixed $n$, in fact we have:

$$\frac{\Delta b_{n,m}}{b_{n,m}} = \xi_E \frac{\Delta A_1}{A_1} - \frac{(\Delta A_1)^2}{2A_1^2}[\xi_E^2(1 + A_1^2) - n^2] \qquad (3)$$

We restrict ourselves to tolerance studies on the second seed laser power, because at the end we want to get a selection criteria on the seed laser wavelength to use, that corresponds to select which harmonics is advantageous to generate. The simulations have been done with the code GENESIS1.3 version 4. For the different simulations only the second seed laser power, that is determining the $A_2$ parameter for the EEHG bunching, has been changed, while all the other parameters (included $A_1$, $B_1$ and $B_2$) have been kept fixed.

### Simulation Results

The tolerance study on the second seed laser power has been pursued for both vis and uv seeds for the case of FEL lasing at 4 nm, which is the most demanding case as we have to achieve a very high harmonic of the seed laser. In fact for the uv seed laser with wavelength of 300 nm is required the 75th harmonic, while for the visible seed laser with wavelength 420 nm the 105th harmonic. The same working point

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for EEHG has been chosen in both cases: $n = -1$, $A_1 = 3$ and $A_2 = 5$. The chicane strengths were higher for the visible case as we were pursuing a higher harmonic.

For this tolerance study, achieved the parameter set giving the maximum bunching, we scanned the $A_2$ parameter by changing the second seed laser power.

In Fig. 3 the two seed lasers performances are compared: on top the uv case and bottom the vis case. Here the bunching variation is represented as a function of the $A_2$ parameter variation from the optimal value $A_2 = 5$. The bunching $\tilde{b}_{n,m}$ and $b_{n,m}$ are the bunching value at the longitudinal position of the electron beam where we have the maximum energy spread at the radiator entrance. The black parabola is the representation of Eq. 2, as expected the parabola for the uv case is wider compared to the vis case, because the target harmonic is smaller. The simulation points overestimate this theory curve in both uv and vis cases. So in order to quantify the sensitivity of the bunching to a $A_2$ variation in the two different cases, we have focused on the region where $\Delta A_2/A_2 \leq 0$ and and we have fitted with a line (red curve). For $\Delta A_2/A_2 > 0$ the seed laser power is too high and thus the central region of the electron bunch has a suppression of the FEL emission, but the sides are lasing, and this results in a double horn FEL power profile as shown in Fig 4. Thus we do not consider these points for the fit. The outcome of the linear fit gives a steepness of $(8.7 \pm 0.8)$ for the uv case and $(9.9 \pm 0.8)$ for the vis case. Thus the vis fluctuation in $A_2$ parameter, so in second seed laser power, affects slightly more the bunching compared to the uv case. Figure 4 is showing in the top plots the FEL power and the correspondent spectra at the position into the radiator were the signal to noise ratio is maximized for three different working points of the tolerance scan: $A_2 = 4.75, 5$ and $5.25$.

## CONCLUSION AND OUTLOOK

Theoretical considerations show that the bunching deviation driven by deviation from the chosen $A_2$ parameter depends on the harmonic number $m$. Therefore it could be a selection criteria for the seed laser wavelength to use in our design. The simulations in the present paper have shown consistence with the theory: the vis case is slightly more sensitive on bunching due to second seed laser power variations, compared to the uv case. Beside theory we have seen that the performances in terms of power and spectral purity are acceptable in both cases. We would conclude that this study is not sufficient to take a final decision on the seed laser wavelength to use. In general, at higher harmonics we are more sensitive on bunching variation due seed laser power fluctuations and the physics of EEHG become more challenging. With a vis seed laser we would need to go down to higher harmonics compared to uv. But, from the laser technology point of view, the vis seed laser is more stable and easier to control compared to the uv, thus it would be easier to keep the power stability.

In conclusion, further studies with a realistic seed laser pulses are foreseen to evaluate the impact of transverse im-

perfection in the beam, and on the electron beam side further investigation on collective effects like incoherent and coherent synchrotron radiation (ISR and CSR) are planned.
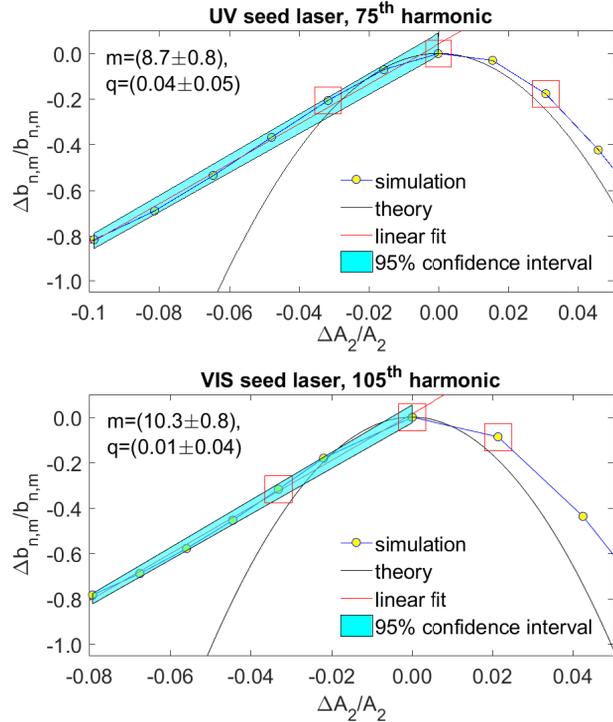


Figure 3: Comparison of relative bunching deviation as a function of the relative deviation in $A_2$ factor between vis and uv seed laser. The red boxes indicated the simulation points selected for Fig. 4.
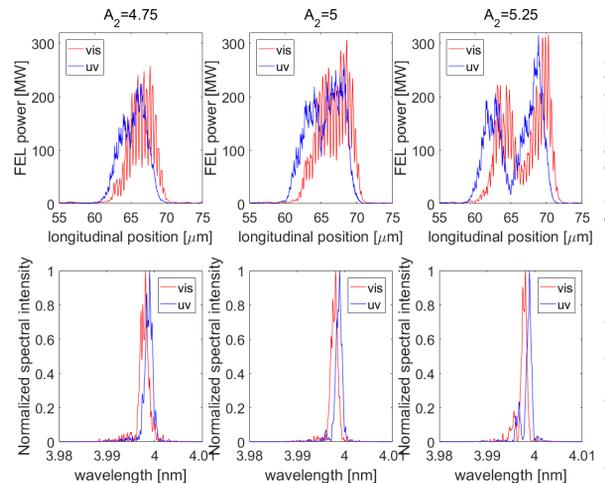


Figure 4: Performance of FEL power as seed laser power is changed for both uv and vis seed lasers.

10th Int. Particle Accelerator Conf.        IPAC2019, Melbourne, Australia        JACoW Publishing

ISBN: 978-3-95450-208-0        doi:10.18429/JACoW-IPAC2019-TUPRB013

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