SEEDED FEL STUDY FOR CASCADED HGHG OPTION FOR FLASH2

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Abstract

The free electron laser (FEL) facility at DESY in Hamburg (FLASH) is the world's first FEL user facility which can produce extreme ultraviolet (XUV) and soft X-ray photons. In order to increase beam time delivered to users, a major upgrade named FLASH II is in progress. As a possibility, a seeding undulator section can be installed between the extraction arc section and the SASE undulator of FLASH2. In this paper, a possible seeding scheme for the cascaded HGHG option for FLASH2 is presented. The SASE undulator of FLASH2 can be used as the second radiator of the cascaded HGHG section. Parameters optimization for the accelerating modules and for the bunch compressors has been done to meet the requirement for the electron bunches. In the beam dynamics simulation, collective effects were taken into account. Particle distribution generated from the beam dynamics simulation was used for the seeded FEL study. Space charge and CSR impacts on the microbunches were included during the cascaded HGHG simulation. The simulation results show that FEL radiation with the wavelength of a few nms and with high monochromaticity can be seeded at FLASH2.

INTRODUCTION

FLASH has been an FEL user facility since 2005 which can produce FEL radiation in the wavelength range from 4.1nm to 45nm [1]. In order to increase the beam time, a major upgrade, FLASH II, is in progress. Behind the main linac, three fast vertical kickers and a DC Septum distribute the electron beam either to the dogleg section of FLASH1 or to the extraction arc of FLASH2 [2]. As the extension of FLASH, the beamline of FLASH2 has been constructed in a separate tunnel. SASE FEL radiation in the wavelength range from 4 nm to 80nm can be produced from the SASE undulator of FLASH2 [3]. Gap of the SASE undulator is variable for relaxing the dependency of the radiation wavelength on the electron beam energy and for independent operation of FLASH1 and FLASH2. As a possibility, a seeding undulator section can be installed between the extraction arc and the SASE undulator of FLASH2. Maybe it can allow for different seeding schemes, like HHG, HGHG and several combinations of them [4]. In this paper, seeded FEL study for the cascaded HGHG option for FLASH2 is presented. The SASE undulator of FLASH2 has been used as the second radiator of the cascaded HGHG in the simulation.

A single stage HGHG section which can also be used as the first stage of the cascaded HGHG consists of a dispersive chicane and two undulator sections: a modulator and a radiator. In the modulator, a seeding laser modulates the electron energy distribution. In the dispersive chicane, the energy modulation is transformed into a density modulation: microbunching. Because the microbunching will have a significant harmonic content, the radiator can be tuned to a higher harmonic of the seed laser. When the bunched electron beam enters the it can emit coherent, intense FEL radiation.

The seed laser which will be used for FLASH2 is a Ti:Sapphire laser at a repetition rate of 100 kHz. After frequency up conversion, the laser wavelength ranges from 200 nm to 270 nm [5]. In the seeded FEL study, the electron beam with energy of 1 GeV has been used and the seeding laser has wavelength of 266 nm. In order to avoid particle loss in terms of FEL bandwidth and to reduce the beam instability due to microbunching, the amplitude of energy modulation in the modulator is limited to less than 1 MeV. Figure 1 gives the estimation of bunching factor as a function of harmonics of the seed laser for different initial uncorrelated energy spread. One can see at the 7^{th} harmonic, the bunching factor can reach 0.2 in the case of 100 keV uncorrelated energy spread. For FLASH, it is possible to obtain electron bunches with a smaller uncorrelated energy spread, when the peak current is low enough. Therefore, in the following study, the peak current of the electron bunch is limited lower than 1.5 kA and the first radiator is tuned to the 7^{th} harmonic of the seed laser.

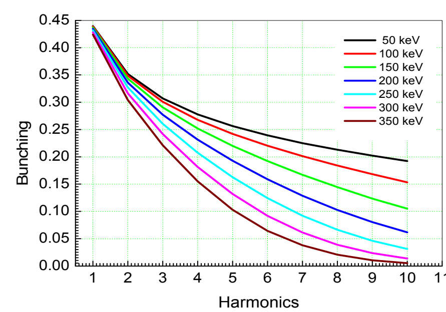

Figure 1: Bunching factor for HGHG with different initial slice energy spreads.

BEAM DYNAMICS SIMULATION

The seed laser has the wavelength of 266nm, the pulse duration is 100 fs and the pulse energy is 6 μJ [5]. The total length of the pulse is about 90 um. In order to get long enough electron bunch for HGHG option, especially for cascaded HGHG, beam dynamics with 1 nC bunch charge case has been studied.

Description of the RF cavities and the magnets is from the FLASH 2 lattice definition which has been written in Elegant format [6].There are some restrictions in the beam dynamics simulation. Same as the normal operation case, the beam energies which were used in the

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simulation before BC2 and BC3 are 145.5 MeV, 450 MeV respectively. The technical restriction of maximum energy gain for each accelerating module has also been taken into account [7].

Transformation of the longitudinal coordinate in the i^{th} bunch compressor can be described with the following formula [8], where R_{56i}, T_{566i} and U_{5666i} are the momentum compaction factors in the i^{th} compressor. δ_i is the relative energy deviation.

$$s_i = s_{i-1} - \left(R_{56i}\delta_i + T_{566i}\delta_i^2 + U_{5666i}\delta_i^3\right) \quad i = 1, \ldots, N$$

For the fixed values of RF parameters and momentum compaction factors, the global compression function can be defined by the following formulas, where $C_N(s)$ describes the increase of the peak current in the slice with initial position s and $Z_N(s)$ is the inverse global compression function.

$$C_N = \frac{1}{Z_N}, Z_N = \frac{\partial s_N}{\partial s}$$

For a two-stage bunch compression scheme, like FLASH, if the collective effects are not included, one can get the relation among the RF parameters, the beam energies and the inverse global compression functions.

$$E_1 = E_1(V_1, \varphi_1, V_{39}\ \varphi_{39}),$$
$$E_2 = E_2(V_1, \varphi_1, V_{39}, \varphi_{39}, V_2, \varphi_2),$$
$$Z_1 = \frac{\partial s_1}{\partial s}(0), Z_2 = \frac{\partial s_2}{\partial s}(0), Z_2' = \frac{\partial^2 s_2}{\partial s^2}(0), Z_2'' = \frac{\partial^3 s_2}{\partial s^3}(0)$$

In the above formulas, V_{39} and φ_{39} are the voltage amplitude and phase shift of ACC39. V_i and φ_i (i=1, 2) are the RF parameters of ACC1 and ACC2-3. In general case, beam bunches are accelerated on crest in ACC4-7. The partial compression functions $C_i = 1/Z_i$ (i=1, 2) describe the amount of the compression achieved after the i^{th} compressor. In principle, for a linear compression in the middle of the bunch, Z_N' and Z_N'' can be set to zero. But they should be adjusted slightly if the collective effects are taken into account.

Typically BC2 is operated with a bending angle of 18° [1]. So the curvature radius of the reference trajectory (r_1) in BC2 has been set to 1.618 m. In order to reduce space charge effects between the BC2 and BC3, a not strong compression (C_1=2.7) in BC2 has been selected in the simulation. Table 1 shows the parameter settings for the bunch compressors. During the parameters selection, the technical restriction of curvature radius [8] has been taken into account. Considering collective effects, a fast tracking code written with matlab was used for the RF parameters optimization. RF settings for the accelerating modules are shown in Table 2. In principle, beam bunches with small energy chirp are needed to get FEL radiation with high monochromaticity. For this purpose, the phase of ACC4-7 was adjusted to obtain beam bunches with small energy chirp.

Table 1: Parameter Settings for the Bunch Compressors

Charge Q, nC	Curvature radius in BC2, r_1 [m]	$R_{56,BC2}$ [mm]	Compr. In BC2	Curvature radius in BC3, r_2 [m]	$R_{56,BC3}$ [mm]	Total compr. C
1.0	1.618	180.7	2.7	5.4	95.7	~20

Table 2: RF Parameter Settings for the Accelerating Modules

V_{acc1} [MV]	φ_{acc1} [deg]	V_{acc39} [MV]	φ_{acc39} [deg]	$V_{acc2,3}$ [MV]	$\Phi_{acc2,3}$ [deg]	$V_{acc4,5,6,7}$ [MV]	$\Phi_{acc4,5,6,7}$ [deg]
160.3	-3.2	21.9	153.4	322.3	19.0	623.0	-28.0

Beam dynamics simulation from the RF gun to the entrance of the first modulator has been completed. For the arc sections, CSRTrack code [9] was used and CSR impact has been taken into account. Beam tracking in the straight sections with space charge effects was simulated by using ASTRA code [10]. The longitudinal cavity wake field effects [11] were included at the exit of each accelerating section with matlab scripts. A million particles were used in the simulation. Figure 2 shows description of the bunch properties before the first modulator. In the middle of the bunch, the maximum uncorrelated energy spread is about 150 keV.

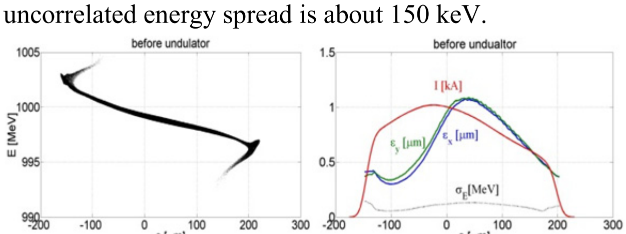

Figure 2: Bunch properties before the modulator for 1.0 nC case. Longitudinal phase space (left), Current profile, slice emittances and slice energy spread (right).

CASCADED HGHG SIMULATION

The technical restriction of K parameter for SASE undulator of FLASH2 can be described as $0.78 \le K_{rms} \le 1.91$. According to the formulas for K parameter $K = \frac{\sqrt{2}}{2} 0.934 B_0[\mathrm{T}]\lambda_u[\mathrm{cm}]$ and for resonant radiation wavelength $\lambda = \frac{\lambda_u}{2\gamma^2}(1 + K^2)$ [12], the reasonable K with different period length for each undulator section has been obtained. The first radiator and the second modulator will have same period length because radiation in them has the same wavelength. Table 3 gives the parameter selections for the undulator sections. It is impossible to tune the second radiator to the 7^{th} harmonic because the K parameter will be out of the limit.

The formula $\hat{I} = \frac{cqkE_{mod}}{\sqrt{\pi}\sigma_E}$ can be used to estimate the peak current of the microbunches after an ideal compression, where E_{mod} is the amplitude of the energy modulation and σ_E is the uncorrelated energy spread. The formula $P_L = 8.7 \times 10^9 \times \left(\frac{E_0 E_{mod}}{511000^2} \cdot \frac{\sigma_{Laser}}{L_u K_{ut}}\right)^2$ gives the relation among the laser power, the beam energy, the

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energy modulation, the size of the laser, the total length and K parameter of the first modulator. Considering the above points, a possible description of the first stage HGHG section is given: The period length of the modulator is 8.3 cm and the total number of periods is 27. There are four dipole magnets in the dispersive chicane. The length of the magnet is 0.1 m, with the same length as FLASH correctors. The distance between the first two dipole magnets is 0.5 m. The radiator has the period length of 4.3 cm and the number of periods is 49. The particle distribution will be up converted to the 7th harmonic of the seed laser in the radiator.

Table 3: Parameter Selections for the Undulator Sections

Undulator sections	λ [nm]	K (rms)	λu [cm]
Modulator 1	266	4.852	8.3
Radiator 1	38	2.402	4.3
Modulator 2	38	2.402	4.3
Radiator 2 (SASE undulator)	12.67 7.6	1.446 0.924	3.14

According to the design optics of FLASH2 SASE option [6], beam optics matching has been done before the SASE undulator. The average beta function in the undulator sections is about 10 meters.

Particle distribution generated from the beam dynamics simulation was used for the radiation study. Simulations in the modulator and in the radiator have been done with Genesis 1.3 [13]. In order to take into account space charge and CSR impacts, ASTRA and CSRTrack codes were used for the beam dynamics simulation on the beamline between the modulator and the radiator. To obtain the input particle files for ASTRA, CSRTrack and Genesis, particle distribution conversion among these codes has been done with matlab scripts. Figure 3 gives the longitudinal phase space at the exit of the first modulator. One can see the amplitude of energy modulation is about 0.8 MeV. An adjustment has been done to shift the laser with respect to the electron bunch to reserve a new part of the bunch for the second stage HGHG.

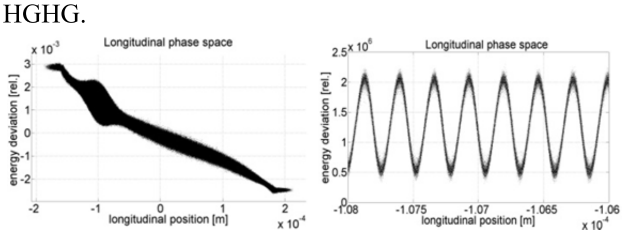

Figure 3: Longitudinal phase space after the modulator.

Before CSRtrack simulation in the first dispersive chicane, some estimation for CSR impact on the microbunches has been done. For an ideal compression, r56 of the chicane should be 53 μm and the curvature radius is 14.5 m. One can get the microbunch length of 8 nm after ideal compression with formula $\sigma = \frac{r_{56}\sigma_E}{E}$. The steady state CSR field [14] has also been estimated. Figure 4 shows the longitudinal field of a microbunch in circular motion. In the center of the bunch, the maximum field is about 18 MV/m. The density modulation and CSR impact on the microbunches in the chicane are shown in Figure 5. One can see the total CSR effect is less than 500 keV.

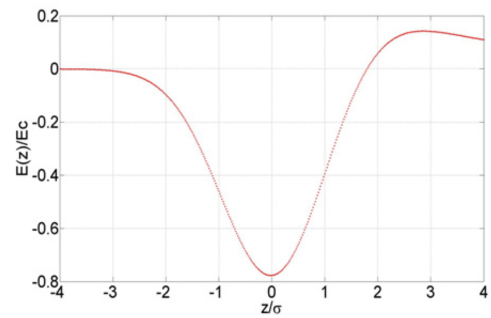

Figure 4: Normalized longitudinal field of an ultra-relativistic thin Gaussian bunch in circular motion.

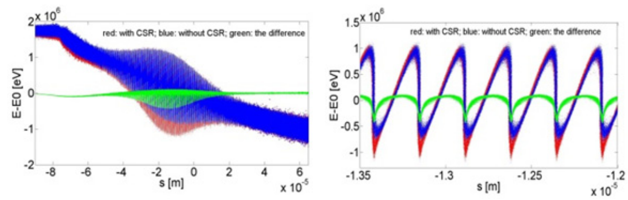

Figure 5: Density modulation and CSR impact on microbunches in the dispersive chicane.

Bunching factor at the entrance of the first radiator and the bunching distribution along the radiator are shown in figure 6. At the exit of the first radiator, radiation with peak power about 0.3 GW has high monochromaticity.

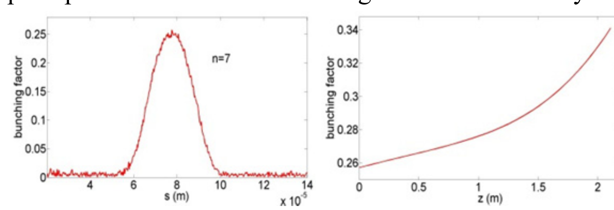

Figure 6: Bunching factor before the radiator (left) and bunching distribution along the radiator (right).

Figure 7 shows the schematic layout of the cascaded HGHG section. A fresh bunch chicane is placed between the first sage and the second. The FEL radiation generated from the first radiator passes the chicane and slips ahead, while the electron bunches are bent on a bump like trajectory and fall behind. Therefore the FEL radiation coincides with a different part of the bunch in the second modulator. This new part has not been seeded before and can be used for the second stage HGHG study. Considering uncorrelated energy spread distribution (Figure 8) after the first radiator, difference between the electron bunch trajectory and the photon pulse trajectory is chosen with a value of 107 μm. Figure 9 shows the longitudinal phase space after the second modulator.

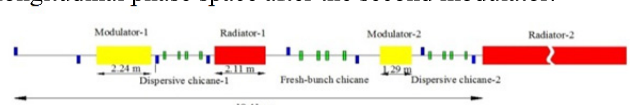

Figure 7: Schematic layout of a cascaded HGHG section.

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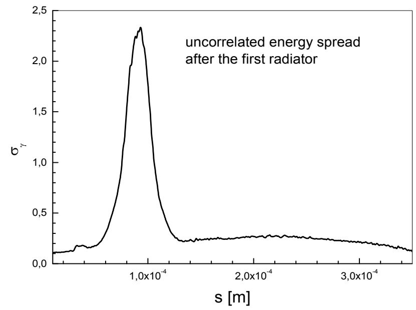

Figure 8: uncorrelated energy spread distribution after the first radiator.

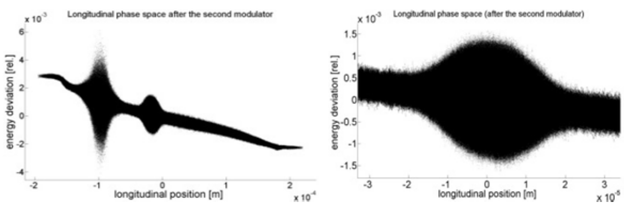

Figure 9: longitudinal phase space after the second modulator.

Before the simulation in the second dispersive chicane, CSR impact on the microbunches has been estimated with the same method like the previous work. r56 of the second dispersive chicane for ideal compression is 5.13 μm and the curvature radius is 47 m. The rms microbunch length after compression is about 1nm. Longitudinal CSR field of a microbunch in circular motion has been estimated. In the center of the bunch, the maximum field is about 4 MV/m. It is not very strength because of the large curvature radius in the chicane. Simulation results show the total CSR effect is less than 100 keV.

In order to obtain high power radiation beyond nominal saturation level, undulator can be tapered to keep the resonant condition as the electron bunches lose energy. It's possible to use tapered undulator for the second radiator because the gap of the SASE undulator of FLASH2 is variable. After adjusting the K parameter of each undulator section, FEL radiation with peak power about 3.5 GW and with high monochromaticity has been obtained when the radiator is tuned to the 3rd harmonic. Bunching factor before the radiator is shown in Figure 10. Figure 11 gives the radiation power at the exit of the radiator and the spectrum. At the exit of the radiator, the radiation energy is about 243 μJ. When the radiator is tuned to the 5th harmonic, one can get the FEL radiation with peak power of 1.0 GW and the resonant wavelength is 7.6 nm.

CONCLUSION

A possible seeding scheme for the cascaded HGHG option for FLASH2 is presented. A start-to-end simulation from the RF gun to the seeding undulator section has been done for this option. Parameters optimization for the accelerating modules and for the bunch compressors was achieved to meet the requirement for the electron bunches. Space charge, CSR and longitudinal cavity wake field effects were taken into account in the simulation. The simulation results show that it is possible to obtain HGHG FEL radiation with the wavelength of a few nms and with high monochromaticity.

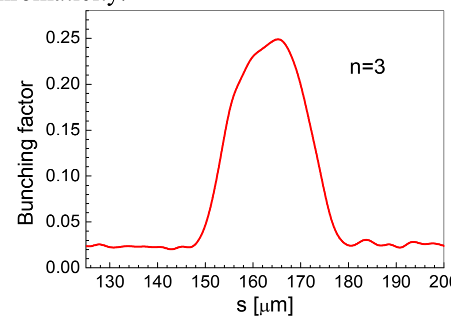

Figure 10: Bunching factor before the second radiator.

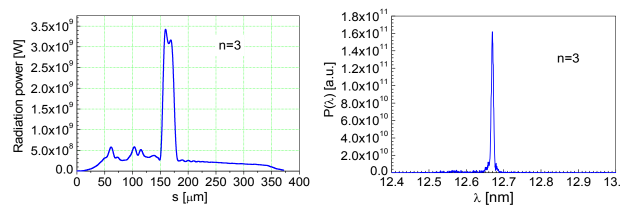

Figure 11: Radiation power at the exit of the radiator (left) and the spectrum (right).

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