BEAM DYNAMICS SIMULATION FOR FLASH2 HGHG OPTION

Guangyao Feng#, Igor Zagorodnov, Torsten Limberg, Martin Dohlus, Winfried Decking, Yauhen Kot, Jörn Boedewadt, Matthias Scholz, Sven Ackermann, DESY, Hamburg, Germany
Kirsten Hacker, Technische Universität Dortmund, Germany
Tim Plath, University of Hamburg, Germany

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 the beam time delivered to users, a major upgrade named FLASH II is in progress. The electron beamline of FLASH2 consists of diagnostic and matching sections and a SASE undulator section. A seeding undulator section will be installed in the future. FLASH2 will be used as a seeded FEL as well as a SASE FEL. In this paper, some results of beam dynamics simulation for the SASE option are given at first which includes parameters selection for the bunch compressors, RF parameters calculation for the accelerating modules and beam dynamics simulation taking into account the collective effects. Beam dynamics simulation for a single stage HGHG option is based on the work for the SASE option. Electron bunches with low uncorrelated energy spread and small energy chirp are obtained after parameters optimization. The FEL simulation results show that 33.6 nm wavelength FEL radiation with high monochromaticity can be seeded at FLASH2 with a 235 nm seeding laser.

INTRODUCTION

In order to increase the beam time, a major upgrade of FLASH, FLASH II, is in progress [1]. As the extension of FLASH, the beamline of FLASH2 has been constructed in a separate tunnel. A seeding undulator section will be installed in the FLASH2 beamline. The layout of the undulator sections will allow for different seeding schemes, like HHG, cascaded HGHG scheme and several combinations of those [2]. In this paper, parameters selection for the bunch compressors, RF parameters calculation for the accelerating sections and beam dynamics simulation taking into account the space charge, CSR and longitudinal cavity wake field effects are introduced for the SASE option. Based on the work for the SASE option, beam dynamics simulation and FEL simulation for a single stage HGHG option are presented. The injector, the main linac, the bunch compressors, the FLASH2 arc section and the beamline between the modulator and the radiator are studied with help of codes ASTRA [3] and CSRTack [4]. Code Genesis 1.3 [5] is used to simulate the physics in the undulator sections.

LAYOUT OF FLASH

The schematic layout of FLASH facility and the magnets distribution in the FLASH2 arc section are shown in Figure 1.

The injector of FLASH consists of a photo cathode RF gun, an L-band accelerating section (ACC1) [6] and a third harmonic accelerating section (ACC39) [7]. There are two accelerating sections, L1 (ACC2, 3) and L2 (ACC4, 5, 6, 7), in the main linac. Two bunch compressor chicanes are installed in horizontal plane along the main linac. The first compressor BC2 is placed downstream of ACC39. It is a C-type chicane which consists of four dipole magnets. The second compressor BC3 is located after ACC3 which has an S-type structure [8, 9].

Behind the main linac, three fast vertical kickers and a DC Lambertson-Septum are installed which can distribute the electron bunches either to the dogleg section of FLASH1 or to the FLASH2 arc section. In the extraction arc of FLASH2, there are four horizontal bending magnets and the arc section is achromatic in horizontal plane. The vertical dispersion caused by the kickers is closed with two vertical bending magnets at the end of the extraction arc. The first order R_{56} parameter becomes zero at the exit of the last dipole magnet [10]. Besides the SASE undulator, a seeding undulator section will be installed in the FLASH2 beamline.

BEAM DYNAMICS SIMULATION FOR SASE

At the entrance of the SASE undulator section, bean bunches with high peak current, small slice emittance and low energy spread are needed to get FEL radiation with short gain length. In the beam dynamics simulation for the SASE option, the peak current of 2.5 kA is used and the beam energy after the main linac is 1.0 GeV. The nominal energies before BC2 and BC3 are fixed as follows: E_1=145.5 MeV, E_2=450 MeV.

The transformation of the longitudinal coordinate in the i^{th} bunch compressor is described by

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

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. For the fixed values of RF parameters and momentum compaction factors, the global compression function can be defined as

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

where, the function $C_N\,(s)$ describes the increase of the peak current in the slice with initial position s and $Z_N(s)$ is the inverse global compression function. For the linear compression in the middle of the bunch, the first and the second derivatives of the global compression can be set to zero. Considering the relation between the derivative of the global compression and the derivative of the inverse

guangyao.feng@desy.de

ISBN 978-3-95450-142-7

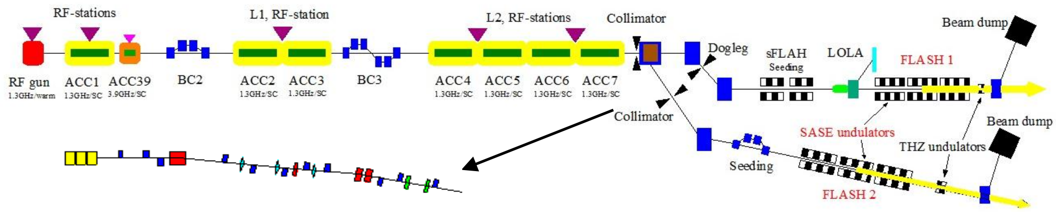

Figure 1: Schematic layout for FLASH facility and the extraction arc of FLASH2.

global compression function [11], we set $Z_N' = 0$ and $Z_N'' = 0$ for the same purpose.

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

$$E_1 = E_1(V_1, \varphi_1, V_{39}\ \ \varphi_{39}),$$

$$E_2 = E_2(V_1, \varphi_1, V_{39}, \varphi_{39}, V_2, \varphi_2),$$

$$Z_1 = \frac{\partial s_1}{\partial s}(0), Z_2 = \frac{\partial s_2}{\partial s}(0), Z_2' = \frac{\partial^2 s_2}{\partial s^2}(0), Z_2'' = \frac{\partial^3 s_2}{\partial s^3}(0)$$

where, 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 L1. In general case, beam bunches are accelerated on crest in L2. The partial compression functions $C_i = 1/Z_i$ (i=1, 2) describe the amount of the compression achieved after the i^{th} compressor.

As an example, the parameters selection for 0.5 nC bunch charge case is given. In this case, the initial peak current after the gun is 26 A and the global compression C of 96 is used. Referring to [8], BC2 is typically operated with a bending angle of 18°. Therefore curvature radius of the reference trajectory in BC2 (r_1) is set to 1.618 m. The technical constraints on the RF voltage for the accelerating modules are taken into account [12], from which we get the maximum voltage of 22 MV for ACC39 and 345 MV for L1. The relation between C_1 and r_2 can be obtained by setting $Z_2' = 0$ and $Z_2'' = 0$. One can see the RF voltage restrictions of ACC39 and L1 in Figure 2. In order to reduce the space charge effects between BC2 and BC3, a not strong compression (C_1=4.7) in BC2 is selected. The working point of r_2 (curvature radius of the

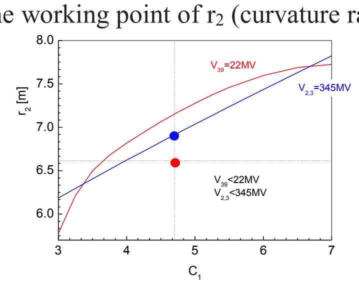

Figure 2: The level lines for voltages.

reference trajectory in BC3) is chosen as a little larger value of 6.60 m for the weaker CSR impact in BC3. At the blue point in figure 2, in order to get beam energy of 450 MeV before BC3, the phase of L1 should be 28°. Therefore at the working point (red point) the phase of L1 is a little smaller than 28°.

Parameter settings for the bunch compressors for 0.5 nC case are shown in Table 1. In the parameters selection process, the restriction of the curvature radius in the compressors [11] has been taken into account.

Vectors $\vec{x}_0$ and $\vec{f}_0$ are defined as follows:

$$\vec{x}_0 = \begin{pmatrix} V_1 \\ \varphi_1 \\ V_{39} \\ \varphi_{39} \\ V_2 \\ \varphi_2 \end{pmatrix}, \ \vec{f}_0 = \begin{pmatrix} E_1 \\ E_2 \\ Z_1 \\ Z_2 \\ Z_2' \\ Z_2'' \end{pmatrix}$$

The relation between $\vec{x}_0$ and $\vec{f}_0$ can be written by using a nonlinear operator A_0: $\vec{f}_0 = A_0(\vec{x}_0)$. If the beam energies and the global compression functions are fixed, the RF parameters can be obtained by using

$$\vec{x}_0 = A_0^{-1}(\vec{f}_0)$$

In reality the RF parameters solution obtained above can not produce the required compression because of the collective effects like space charge and CSR [11]. In order to take these effects into account a fast tracking code written in matlab language is used. The RF parameter settings for the accelerating modules are shown in Table2.

The beam dynamics simulation from the RF gun to the entrance of the SASE undulator has been done with a million particles. For all of the arc sections, CSRTrack code is used taking into account the CSR impact. The beam tracking in the straight sections is simulated with ASTRA code. Longitudinal cavity wake field effects [13, 14] are considered at the exit of each accelerating section with matlab scripts. Figure 3 gives description of the beam bunch properties at the entrance of SASE undulator.

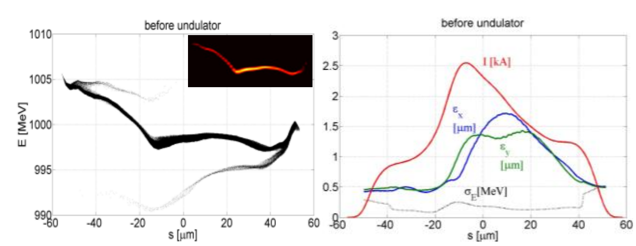

Figure 3: Beam bunch properties before SASE undulator. Longitudinal phase space (left), Current profile, slice emittances and slice energy spread (right).

Table 1: Parameter settings for the bunch compressors

Charge Q, [nC]	r_1 in BC2, [m]	$R_{56,BC2}$, [mm]	Compr. in BC2	r_2 in BC3, [m]	$R_{56,BC3}$, [mm]	Total compr.
0.5	1.618	180.7	4.7	6.60	63.8	96

Table 2: RF parameter settings for the accelerating modules

Charge [nC]	V_{acc1} [MV]	φ_{acc1} [deg]	V_{acc39} [MV]	φ_{acc39} [deg]	$V_{acc2,3}$ [MV]	$\Phi_{acc2,3}$ [deg]	$V_{acc4,5,67}$ [MV]
0.5	159.5	2.4	19.8	162.6	337.3	25.0	550.0

SIMULATION FOR HGHG OPTION

In the simulation for a single stage HGHG option, seeding laser with wavelength of 235 nm, pulse duration of 30 fs and peak power of 125 MW is used [15]. According to [16], the peak current of the electron beam is limited to 1.5 kA and the radiator is tuned to the 7th harmonic of the seed wavelength. Beam dynamics simulation for the HGHG option is based on the work for the SASE option. Since the RF parameters of ACC1 and ACC39 are sensitive to the global compression and the current density distribution, we don't want to adjust them once they have been optimized for a linear longitudinal phase space. In principle, one can use low longitudinal compression in BC3 to get electron bunches with small uncorrelated energy spread. Beam bunches with small energy chirp are needed to get FEL radiation with high monochromaticity. For this purpose, smaller phase shift of L1 has been used to reduce the voltage requirement on L2 and the phase of L2 is adjusted to obtain beam bunches with small energy chirp. Figure 4 gives description of the bunch properties before the modulator section. In the middle of the bunch, the maximum value of uncorrelated energy spread is about 100 keV.

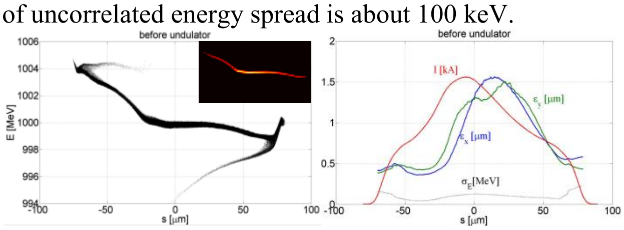

Figure 4: Beam bunch properties before the modulator for HGHG. Longitudinal phase space (left), Current profile, slice emittances and slice energy spread (right).

As one feasible scheme, the period length of the modulator is 6.7 cm and the total number of periods is 30. The radiator has the period length of 3.14 cm and the number of periods is 152. According to the design optics for the SASE option [17], beam optics matching has been done before the SASE undulator section. ASTRA and CSRTrack codes are used in the beam dynamics simulation for the beamline between the modulator and the radiator to take into account the space charge and CSR impacts. From the pictures of longitudinal phase spaces in the middle of the bunch (Figure 5), one can see the energy modulation after the modulator and the density modulation after the dispersive chicane.

The R_{56} parameter in the chicane has been scanned to get FEL radiation with high energy. The results show that the radiation energy can reach maximum value when the R_{56} is 41.6 μm. For this case, bunching factor at the 7th harmonic of the seed wavelength before the radiator is shown in Figure 6. Over compression in the middle of the bunch can be seen. In this simulation, strong space charge impact can not be seen (Figure 6) at the entrance of the radiator because of the short distance between the chicane and the radiator.

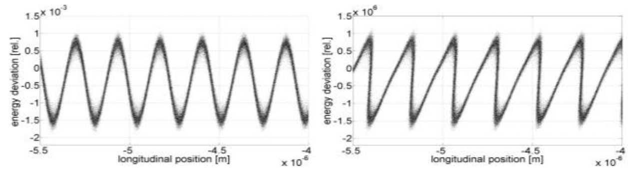

Figure 5: Longitudinal phase spaces after the modulator (left) and after the dispersive chicane (right).

At the exit of the radiator, the FEL radiation with peak power about 3.3 GW has high monochromaticity (Figure 7 (right)). Figure 7 (left) shows the radiation energy along the radiator. The energy is about 118 μJ after the radiator.

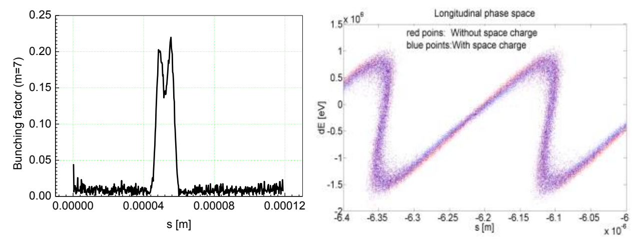

Figure 6: Bunching factor (left) and longitudinal phase space (right) at the entrance of the radiator.

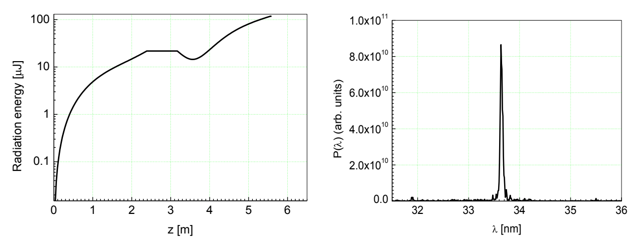

Figure 7: Radiation energy along the radiator (left) and the spectrum (right).

CONCLUSION

In the paper, the beam dynamics simulation for FLASH2 SASE option is introduced which includes the parameters selection for the bunch compressors, the RF parameters calculation for the accelerating modules and the beam dynamics simulation taking into account the collective effects. The beam dynamics simulation for the HGHG option is based on the work for the SASE option. In order to get FEL radiation with several GW power and with high monochromaticity, parameter settings for the accelerating modules and for the bunch compressor have been optimized. The results show that 33.6 nm wavelength FEL radiation can be seeded at FLASH2 with a 235 nm seeding laser.

ACKNOWLEDGMENT

The authors of this paper would like to thank Bart Faatz, Sven Reiche, Velizar Miltchev, Sascha Meykopff for their support and help for this work.

REFERENCES

[1] B. Faatz, et al., "FLASH II: A seeded future at FLASH", Proceedings of IPAC, Kyoto, Japan (2010).
[2] K. Hacker, "A Concept for Seeding 4-40 nm FEL Radiation at FLASH2", TESLA-FEL, 2013-01.
[3] K. Floettmann, "ASTRA", DESY, Hamburg, http:// www.desy.de/~mpyflo/, (2011).
[4] M. Dohlus,T. Limberg, "CSRtrack: faster calculation of 3D CSR effects", Proceedings of FEL, Italy (2004)
[5] S. Reiche, "GENESIS 1.3", NIM A 429 (1999) 243.
[6] J. Iversen, R. Bandelmann, et al., "A Review of the 1.3GHz Superconducting 9-cell cavity Fabrication for DESY", Proceedings of LINAC Conference, Tsukuba (2010).
[7] M. Dolus, "FLASH beam dynamics issues with 3rd harmonic system", MAC meeting, DESY (2009).
[8] M. Vogt, B. Faatz, et al., "Status of the free electron laser FLASH at DESY", Proceedings of IPAC, Spain (2011).
[9] M. Vogt, B. Faatz, et al., "The free electron laser FLASH at DESY", Proceedings of IPAC, China (2013).
[10] M. Scholz, W. Decking, et al., "Extraction arc for FLASH II", Proceedings of FEL, Japan (2012).
[11] I. Zagorodnov, M. Dohlus, "A semi-Analytical Modelling of Multistage Bunch Compression with Collective Effects", Physical Review STAB 14 (2011).
[12] http://www.desy.de/fel-beam/s2e/flash/Information/RF.txt
[13] T. Weiland, I. Zagorodnov, "The short-range transverse wake function for Tesla accelerating structure", TESLA Report 2003-19, DESY (2003).
[14] I. Zagorodnov, T. Weiland, M. Dohlus, "Wake fields generated by the LOLA-IV Structure and the 3rd Harmonic section in TTF-II", TESLA Report 2004-01, DESY (2004).
[15] T. Tanikawa, "Seeding Preparation at the FLASH2 Beamline", Proceedings of FEL, Basel, Switzerland (2014).
[16] G. Feng, I. Zagorodnov, et al., "Start to end simulation for FLASH2 HGHG option", Proceedings of FEL, Basel, Switzerland (2014).
[17] M. Scholz, FLASH-lattice files, http://www.desy.de/fel-beam/ flash2_elegant_2012_09_19.zip