START-TO-END SIMULATION FOR FLASH2 HGHG OPTION

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Abstract

The Free-electron laser in Hamburg (FLASH) is the first FEL user facility to have produced extreme ultraviolet (XUV) and soft X-ray photons. In order to increase the beam time delivered to users, a major upgrade of FLASH named FLASH II is in progress. The electron beamline of FLASH2 consists of diagnostic and matching sections, a seeding undulator section and a SASE undulator section. In this paper, results from a start-to-end simulation for a FLASH2 High-Gain Harmonic Generation (HGHG) option are presented. For the beam dynamics simulation, space charge, coherent synchrotron radiation (CSR) and longitudinal cavity wake field effects are taken into account. In order to get electron beam bunches with small correlated and uncorrelated energy spread, RF parameters of the accelerating modules have been optimized as well as the parameters of the bunch compressors. Radiation simulations for the modulator and the radiator have been done with code Genesis 1.3 by using the particle distribution generated from the beam dynamics simulation. The results show that for a single stage HGHG, 33.6 nm wavelength FEL radiation can be seeded at FLASH2 with a 235 nm seeding laser.

INTRODUCTION

FLASH has been an FEL user facility since 2005 which can produce XUV and soft X-ray radiation in the wavelength range from 4.1nm to 45nm [1, 2]. In order to increase the beam time, a major upgrade, FLASH II is in progress which will provide seeded FEL radiation as well as SASE FEL radiation [3]. At the exit of the existing linear accelerator, as the extension of FLASH, FLASH2 was built in a separate tunnel. With fast kickers and a DC Lambertson septum, parts of the electron bunch trains generated from the main linac can be extracted into the FLASH2 arc and then pass through the undulator sections. The undulator sections will consist of the seeding undulator section and the SASE undulator section. The layout of the seeding undulator section which will be installed between the extraction arc and the SASE undulator section allows for different seeding schemes, like HHG, HGHG and several combinations of those [4]. The SASE undulator can also be used as the final radiator for the cascaded HGHG scheme and as the amplifier for a direct seeding with HHG. For independent operation of FLASH1 and FLASH2, all FLASH2 undulators will have variable gap to relax the dependency of the radiation wavelength on the electron beam energy.

In this paper, some results of a start-to-end simulation for FLASH2 single stage HGHG option are presented. The injector, the accelerator, the bunch compressors and the extraction arc are studied with help of the codes ASTRA [5] and CSRTrack [6]. Space charge, CSR and longitudinal cavity wake field effects have been taken into account in the beam dynamics simulation. FEL simulations in the modulator and the radiator have been done with Genesis 1.3 [7] by using the particle distribution generated from the beam dynamics simulation. In order to consider the space charge and CSR impacts in the seeding section, the dispersive chicane and the straight beamline between the modulator and the radiator have been simulated with CSRTrack and ASTRA respectively.

LAYOUT OF FLASH

The injector of FLASH consists of a RF gun, an L-band accelerating section and a third-harmonic accelerating section. Electron bunches are generated from a photo cathode by the laser beam and accelerated to 5 MeV by a normal conducting 1.3 GHz RF gun. After the gun, the electron bunches are accelerated in a single TESLA type module named ACC1 [8]. Downstream of ACC1 section a third-harmonic (3.9 GHz) RF system named ACC39 can linearize the RF curvature distortion and minimize the beam tails in the next chicanes [9]. In the L-band superconducting linear accelerator, there are two accelerating sections named L1 and L2 with 1.3 GHz. These two sections are separated by a bunch compressor. L1 has 2 modules (ACC2-3) and L2 has 4 (ACC4-7). There are two bunch compressor chicanes in horizontal plane along the main linac. The first bunch compressor BC2 is located downstream of ACC39. The second bunch compressor BC3 is placed after ACC3 which has an S-type structure (Figure 1).

Behind the main linac of FLASH, three fast vertical kickers and a DC Lambertson-Septum distribute the beam either to the dogleg section of FLASH1 or to the new extraction arc of FLASH2. There are four horizontal bending magnets in the extraction arc of FLASH2 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 compaction factor (R_{56}) becomes zero at the end of last dipole magnet by using a reverse bending magnet and the proper distribution of dispersion function in the extraction arc section [10]. The undulator

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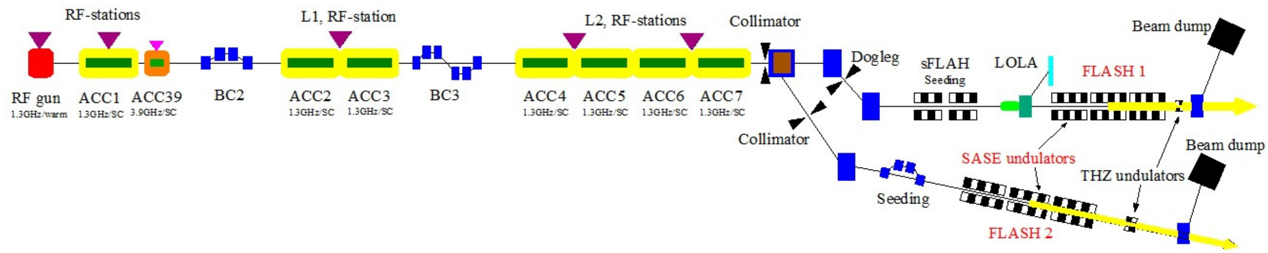

Figure 1: Schematic layout of FLASH facility.

system of FLASH2 will include a seeding undulator section and a SASE undulator section.

BEAM DYNAMICS SIMULATION

The optimization and simulation for a single stage HGHG for FLASH2 have been done. The single stage HGHG section consists of two undulator sections and a dispersive chicane. In the first undulator section, the modulator, a seed laser modulates the electron energy distribution. In the dispersive chicane, the energy modulation is transformed into a density modulation: microbunching. Because the microbunching can have a significant harmonic content, the second undulator section, the radiator, can be tuned to a higher harmonic of the seed wavelength. When the bunched electron beam enters the radiator, it can emit coherent, intense FEL radiation.

The seed laser which will be used for HGHG is a Ti:Sapphire laser at a repetition rate of 100 kHz. After frequency up conversion, the seeding wavelength ranges from 200 nm to 270 nm [11]. In this simulation the electron beam energy is 1 GeV and the seeding laser has wavelength of 235 nm, pulse duration of 30 fs and peak power of 125 MW. In order to avoid particle loss in terms of FEL bandwidth, the energy modulation in the modulator is limited to less than 3 MeV (peak-to-peak). Figure 2 gives the estimation of the bunching factor as a function of harmonics of the seed wavelength for different initial uncorrelated energy spread. One can see at the 7^{th} harmonic, the bunching factor can reach 0.2 in 100 keV slice energy spread case.

For FLASH, it is possible to obtain an electron beam bunch with an uncorrelated energy spread in the range of 100 to 150 keV, when the peak current is about 1.5 kA. Therefore, the peak current of the electron beam is limited to about 1.5 kA and the radiator is tuned to the 7^{th} harmonic of the seed wavelength.

An example of the electron beam bunch from start-to-end simulations, with 0.5 nC charge, is shown below. The beam energy is 1.0 GeV and the peak current is about 1.5 kA. The technical constraints on the RF voltage for the accelerating modules have been considered for the RF parameter settings [12].

For the 0.5 nC case, the initial peak current at the gun is about 26 A and a global compression factor [13], C, of 58 is used. Referring to [1], BC2 is typically operated with a bending angle of 18°. So the curvature radius of the reference trajectory (r_1) in BC2 has been set to 1.618 m. In order to reduce the space charge effects between the BC2 and BC3, a not strong compression (C_1=4.7) in BC2

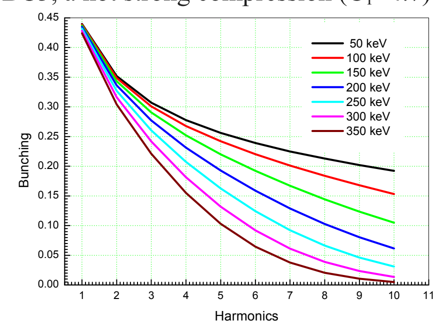

Figure 2: Bunching factor for HGHG with different initial slice energy spreads.

has been used in the simulation. Parameter settings for the bunch compressors are shown in Table 1. During parameter selection, the restriction of curvature radius ($1.4\ \mathrm{m} \leq r_1 \leq 1.93\ \mathrm{m},\ 5.3\ \mathrm{m} \leq r_2 \leq 16.8\ \mathrm{m}$) [13] has been taken into account.

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 order to get HGHG radiation with high monochromaticity, electron beam bunches with small energy chirp are needed. For this purpose, smaller phase shift of L1 has been used to reduce the voltage requirement on L2. Additionally, L2 phase adjustment is helpful to obtain bunches with small energy chirp at the end of the linac.

In reality the RF parameters solution obtained from the relation among the RF parameters, the beam energy and the global compression functions cannot produce the required compression because of the collective effects [13]. In order to take these effects into account a fast tracking code written in the MATLAB language has been used. The RF parameter settings for the accelerating modules are shown in Table 2.

Beam dynamics simulation from the gun to the entrance of the modulator has been done for the 0.5 nC case. For all of the arc sections, like BC2, BC3 and the extraction arc, CSRTrack code is used. The beam tracking in the straight sections (including RF accelerating modules) with space charge effects is simulated with ASTRA code. For the ASTRA simulation, the 3D calculation has been used in order to get results with higher credibility. The

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Table 1: Parameter Settings for the Bunch Compressors

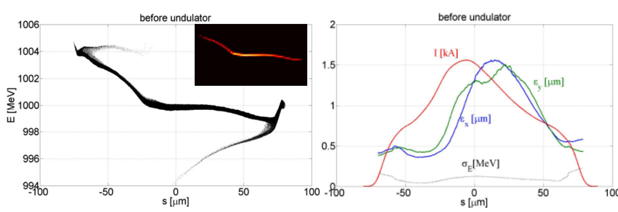
Charge Q, nC	Curvature radius in BC2, r_1 [m]	$R_{56,BC2}$ [mm]	Compr. In BC2	Curvature radius in BC3, r_2 [m]	$R_{56,BC3}$ [mm]	Total compr. C
0.5	1.618	180.7	4.7	6.18	72.8	58

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]	$V_{acc4,5,67}$ [MV]	$\Phi_{acc4,5,6,7}$ [deg]
159.5	2.4	19.8	162.6	323.3	19.0	623.0	-28.0

longitudinal cavity wake field effects [14, 15] have been taken into account at the exit of each accelerating section by using matlab scripts. A million particles are used in the simulation. The model of the RF gun which generates the Gaussian distribution current profile is from [16].

Beam bunch properties (longitudinal phase space, current profile, slice emittances and slice energy spread) at the entrance of the modulator section are shown in Figure 3. The maximum slice energy spread is about 100 keV. The projected emittance is 1.18 μm in horizontal plane and 1.16 μm in vertical plane.



(a) (b)

Figure 3: Beam bunch properties before the modulator section for 0.5 nC case. (a) Longitudinal phase space. (b) Current profile, slice emittances and slice energy spread.

RADIATION SIMULATION FOR HGHG

Figure 4 gives a schematic layout of the seeding undulator section. The period length of the modulator is 6.7 cm and the total number of periods is 30. In the dispersive chicane, there are four dipole magnets. 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 3.14 cm and the number of periods is 152. It is separated into 2 parts by using one quadrupole magnet. The particle distribution can be up converted to the 7th harmonic of the seeding wavelength in the radiator. There are spaces reserved for installation of a fresh bunch chicane, a second modulator and a second dispersive chicane for a cascaded HGHG option.

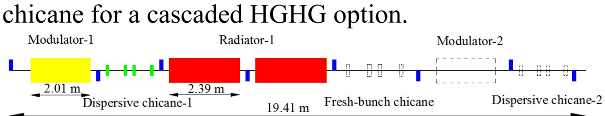


Figure 4: Schematic layout of the seeding undulator section.

An alternating gradient quadrupole lattice provides the electron beam focusing. According to the design optics for FLASH2 SASE option [17], beam optics matching has been done before the SASE undulator section (the second radiator) by using the quadrupole magnets in the seeding undulator section. Betatron functions are shown in Figure 5. One can see the average beta function in the undulator section is approximately 10 meters.

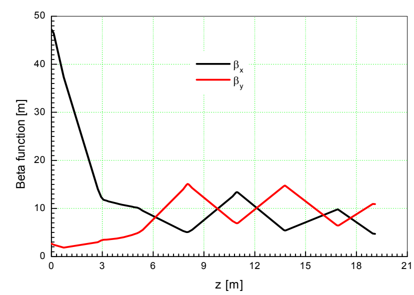


Figure 5: Betatron function in the seeding undulator section.

Particle distribution generated from the above beam dynamics simulation is used for the radiation simulation. Simulation in the modulator and the radiator has been done with Genesis 1.3. In order to take into account the space charge and CSR impacts, we use ASTRA and CSRTrack codes to do the beam dynamics simulation for the beamline between the modulator and the radiator. To obtain the input particle files, particle distribution conversion between ASTRA and Genesis 1.3 has been done by using matlab scripts.

At the exit of the modulator, the longitudinal phase space is shown in Figure 6 from which one can see the energy modulation. An adjustment has been done to shift the seeding laser with respect to the electron bunch.

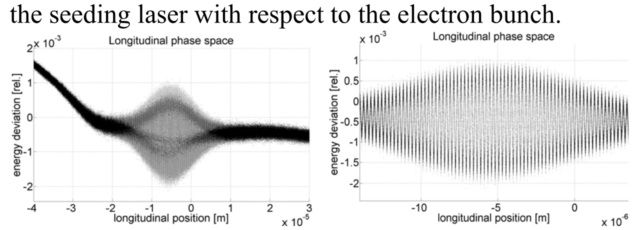


Figure 6: Longitudinal phase space after the modulator.

From the above pictures one can see there is an amplitude distribution of the energy modulation. In order to get FEL radiation with high energy, the R_{56} parameter in the chicane has been scanned. Figure 7 gives the radiation energy at the exit of the radiator for different R_{56} parameters. The energy can reach maximum value when the R_{56} parameter is 41.6 μm. Therefore the following simulation results are given for this case. The bunching factor (the 7th harmonic of seeding wavelength) at the entrance of the radiator and the bunching distribution along the radiator are shown in Figure 8. One can see the

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over compression in the middle of the bunch. At the exit of the radiator, the radiation with peak power about 3.3 GW has high monochromaticity (Figure 9). Figure 10 gives the radiation energy along the radiator. The energy is about 118 μJ after the radiator.

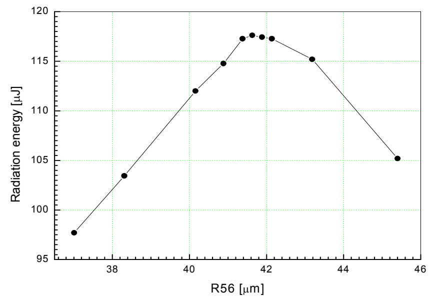

Figure 7: Radiation energy at the exit of the radiator as a function of R_{56} in the chicane.

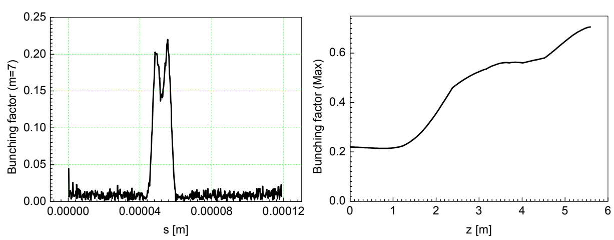

Figure 8: Bunching factor at the entrance of the radiator (left), Bunching vs. z in the radiator (right).

Due to the density modulation, the space charge impact after the dispersive chicane is important because it can cause distortion of the bunch distribution. In this simulation strong space charge impact can not be seen at the entrance of the radiator because of the short distance between the chicane and the radiator. The simulations above are aimed at the cascaded option. If one intends for the HGHG option to operate in a stand-alone fashion, in order to obtain FEL beam with optimal performance delivered to users, maybe it is necessary to let the microbunched beam drift over a significant distance to reach the last radiator section prior to the user beamline. Some issues like LSC, CSR, R_{53} and R_{54} impacts should be considered for that option [18].

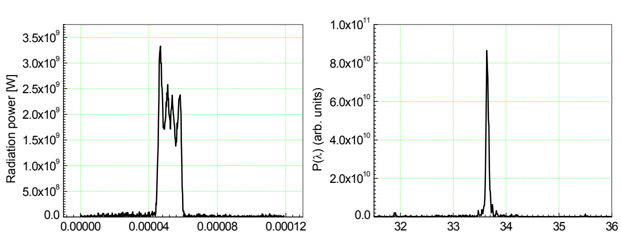

Figure 9: Radiation power at the exit of the radiator (left) and the spectrum (right).

CONCLUSION

FLASH2 will be used as a seeded FEL source. One feasible scheme for single stage HGHG option is given in this paper. In order to get HGHG radiation with several GW power and with high monochromaticity, parameter settings for the accelerating modules and the bunch compressors have been optimized. Space charge, CSR and longitudinal cavity wake field impacts are taken into account in the start-to-end simulation. The results show that 33.6 nm wavelength FEL radiation can be seeded at FLASH2 with a 235 nm seeding laser.

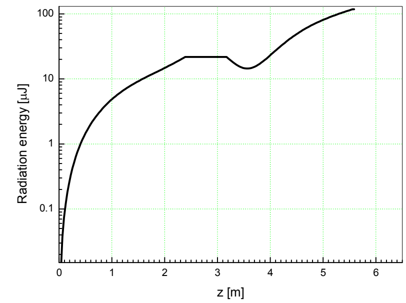

Figure 10: Radiation energy along the radiator.

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