ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOMS024

SENSITIVITY OF EEHG SIMULATIONS TO DYNAMIC BEAM PARAMETERS

D. Samoilenko*, W. Hillert, F. Pannek
University of Hamburg, 20148 Hamburg, Germany
S. Ackermann, E. Ferrari, N. Mirian, P. Niknejadi, G. Paraskaki, L. Schaper
Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany
F. Curbis, M. Pop, S. Werin, Lund University & MAX IV Laboratory, 22363 Lund, Sweden

Abstract

Currently, the Free electron laser user facility FLASH at DESY is undergoing a significant upgrade involving the complete transformation of one of its beamlines to allow external seeding. With the Echo-Enabled Harmonic Generation (EEHG) seeding method, we aim for the generation of fully coherent XUV and soft X-ray pulses at wavelengths down to 4 nm. The generated FEL radiation is sensitive to various electron beam properties, e.g., its energy profile imprinted either deliberately or by collective effects such as Coherent Synchrotron Radiation (CSR). In dedicated particle tracking simulations, one usually makes certain assumptions concerning the beam properties and the collective effects to simplify implementation and analysis. Here, we estimate the influence of some of the common assumptions made in EEHG simulations on the properties of the output FEL radiation, using the example of FLASH and its proposed seeding beamline. We conclude that the inherent properties of the FLASH1 beam, namely the negatively chirped energy profile, has dominant effect on the spectral intensity profile of the radiators output compare to that of the CSR induced chirp.

INTRODUCTION

Echo-Enabled Harmonic Generation (EEHG) [1] is an external seeding technique for Free Electron Lasers (FEL). In comparison with the classical Self Amplified Spontaneous Emission (SASE) scheme, seeding techniques offer temporally coherent, narrow-bandwidth FEL radiation with much better shot-to-shot stability [2]. In comparison with other seeding schemes, EEHG provides higher conversion efficiency at high harmonics of the seed laser wavelength and more robustness with respect to the initial beam quality [3]. FLASH2020+ [4] is a major upgrade of the existing FLASH (Free electron LASer in Hamburg) facility, which includes the reconstruction of the FLASH1 beamline to allow external seeding. The EEHG option in FLASH1 beamline will be used to generate soft X-ray radiation with wavelengths down to 4 nm. The realization of EEHG is more challenging at shorter wavelengths because of the precise phase space transformations in the dedicated seeding section of the beamline at higher harmonics. The essential components of the seeding section are the two modulators and the two magnetic chicanes, as depicted in Fig 1. Each component induces specific longitudinal energy correlations, which have to be carefully chosen and transported through the beamline. Any deviations from the design beam parameters at each point of the beamline could have a detrimental effect on the performance of EEHG-based FEL. Therefore, it is crucial to investigate this section's dynamic beam parameters in detail. Particle tracking simulations are a widely used tool for investigating beam dynamics, which can help anticipate detrimental effects and indicate ways of mitigating them. At the same time, the accuracy of the simulations in each particular case is restricted by the underlying approximations and assumptions. Some of these assumptions are related to the functionality of the simulation code. For example, in EEHG simulations performed with `Genesis 1.3` [5] the effect of Coherent Synchrotron Radiation (CSR) in the chicanes is not taken into account, even though it can have a noticeable effect on the electron beam parameters [6]. Other assumptions are made deliberately by the user to make the implementation or interpretation of the simulations more straightforward. For example, while tracking the electron beam through the EEHG seeding section with `elegant` [7], one can neglect the initial electron beam energy chirp. The effect of the initial electron beam energy modulations on EEHG itself is well studied elsewhere (see, e.g., [8]), but an interplay between the initial chirp and the modulations induced by the CSR might be possible. In this work, we use the example of the future EEHG beamline at FLASH to see how the assumptions mentioned above can change the properties of the output FEL radiation.

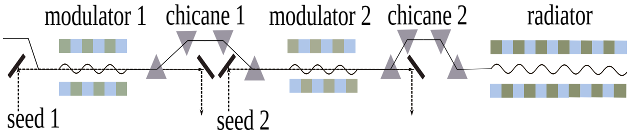

Figure 1: Schematic of the simulated setup.

METHODS

The simulations are performed in two steps. First, we start at the entrance of the first EEHG modulator, where the electron distribution is generated by `elegant` according to the beam parameters specified in Table 1. Two ideal matched initial electron beam distributions are considered: in one, the energy chirp is 0 MeV/ps (no chirp), and in the other −15 MeV/ps, which is the expected value for 4 nm working

---

[*] dmitrii.samoilenko@desy.de

point in FLASH1. All other beam parameters are the same. The beam is then tracked in `elegant` through the seeding section (shown in Fig. 1) up to the entrance of the radiator section. The parameters of the seeding section are given in the Table 1, where $A_{1,2}$ is the energy modulation in terms of the initial energy spread in the first and the second modulator respectively and $R_{56}^{(1,2)}$ is the dispersion strength of the first and the second chicane respectively. In this work, we neglect the CSR in the second chicane as well as in both modulators, because it is expected to be much less pronounced than in the strong first chicane. The CSR in the first chicane is calculated by the built-in method [9] implemented in `elegant`'s `CSRCSBEND` element. The method uses 1D-model to calculate longitudinal CSR-induced energy kicks along the dipoles of the chicane and applies them to the electron bunch. The model calculates the CSR in free space, ignoring the effect of the resistive chamber walls of the chicane. The effect of shielding and wakefields from the chamber walls will be considered in future work. Further information about the element and the application of the model can be found in `elegant`'s manual [10].

The particle distribution at the entrance of the first radiator, produced by `elegant`, is then converted into the format of `GENESIS` particle distribution and imported into the simulation for the radiator section. The most important parameters of the radiator are also given in Table 1.

Table 1: Simulation Parameters

Initial beam parameters	
Central energy	1350 MeV
Slice energy spread	150 keV
Bunch length rms	96 μm
Peak current	500 A
Normalized emittance	0.6 mm·mrad
Seeding section parameters	
Seed lasers wavelength	300 nm
A_1	3.10
$R_{56}^{(1)}$	7.05 mm
A_2	5.18
$R_{56}^{(2)}$	81.25 μm
Radiator section parameters	
Target wavelength	4 nm
Length	2.508 m × 11
Undulator period	3.3 cm

RESULTS AND DISCUSSION

Figure 2 (a) shows the energy profile of the initial electron beam with (dashed blue line) and without (solid blue line) the initial −15 Mev/ps energy chirp. The plot also shows the current profile (solid black line) for the reference. Figure 2 (b) shows the energy profile of the electron beam at the exit of the first chicane in the cases with (orange lines) and without (blue lines) the CSR effect. From the plot, we see that the energy profile of the electron beam changes in the presence of the CSR especially in the region of the high current. Based on the results of [6] we expect an effect on the spectrum of the output FEL radiation. One can also see from the plot that the amplitude of the CSR-induced energy modulation is much smaller than the initial chirp.

Figure 3 shows the spectrum of the FEL output in the vicinity of the target wavelength when power saturation in the radiator is reached. From the plot, we immediately see that the quality of the spectrum has deteriorated because of the CSR-induced energy modulation. Despite the complex shape of the spectrum, we see indications that the maximum radiation power is shifted due to the CSR (see Table 2). We also estimate the RMS bandwidths of the spectra, which are given in Table 3. From this consideration, we conclude that the RMS bandwidth of the FEL radiation changes by one order of magnitude for the unchirped electron beam due to the CSR. Finally, we repeat the simulations for the case when the initial electron beam has a linear chirp of

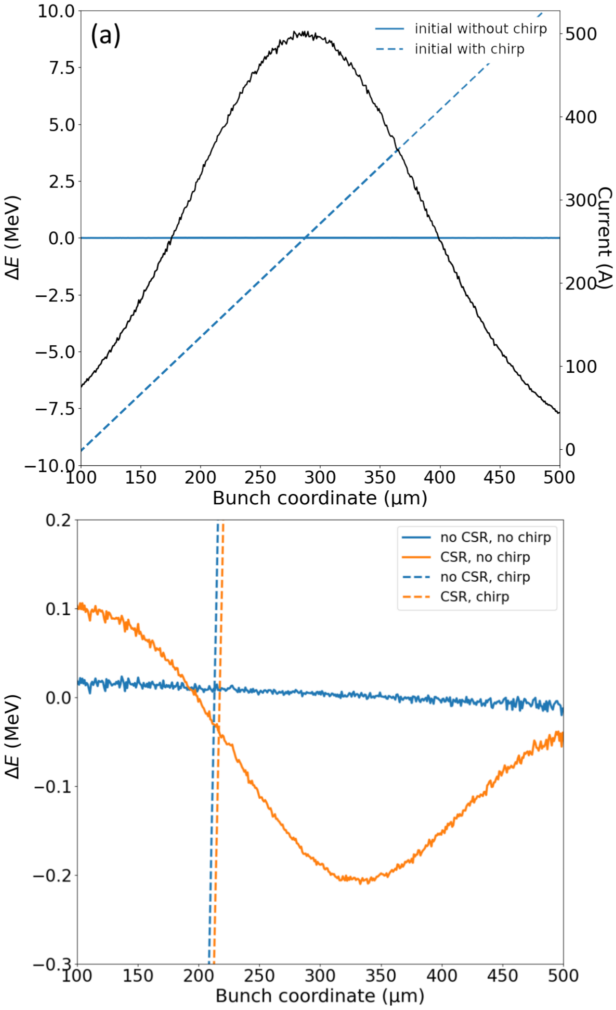

Figure 2: (a) - Energy profile of the initial electron beam with the current profile (solid black line); (b)- Energy profile of the electron beam at the exit of chicane 1. The head of the bunch is on the left.

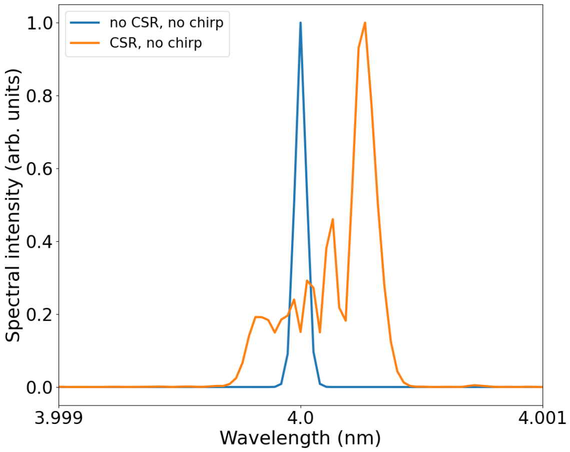

Figure 3: Spectral shape of the EEHG FEL pulse in the saturation mode in the case of no initial electron beam energy chirp.

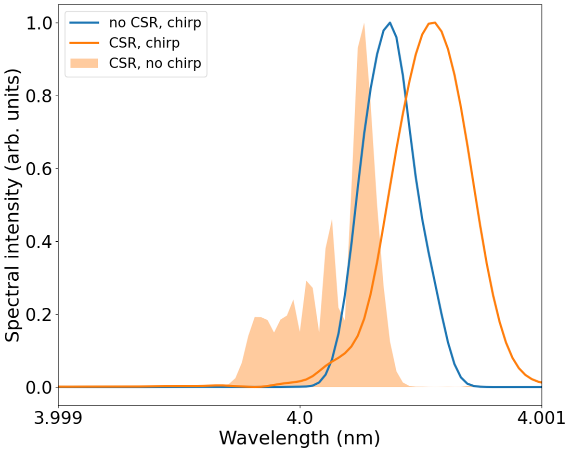

Figure 4: Spectral shape of the EEHG FEL pulse in the saturation mode in the case of 15 MeV/ps initial electron beam energy chirp.

Table 2: Resonant Wavelength Shift

Initial chirp	**no CSR** (10^{-4}**nm**)	**CSR** (10^{-4}**nm**)
0 MeV/ps	-	2.66 (0.007%)
−15 MeV/ps	3.73 (0.009%)	5.31 (0.013%)

Table 3: RMS Bandwidths of the Output FEL Spectra

Initial chirp	**no CSR** (10^{-4}**nm**)	**CSR** (10^{-4}**nm**)
0 MeV/ps	0.17	1.31
−15 MeV/ps	0.81	1.11

−15 MeV/ps. Figure 4 shows the spectral shapes with (solid orange line) and without (solid blue line) the CSR for the initially chirped electron beam. The plot also includes the spectrum for the CSR-affected unchirped beam (shaded orange) from Fig. 3 for the reference. One can see that the multiple peak structure is not observed in the spectrum with the chirp present. This result is in agreement with the theory from [6], that the multiple peaks in the spectrum originate from the regions of the bunch, which have different local chirp values. When a relatively strong initial linear chirp dominates the electron beam energy profile, this mechanism of spectral broadening is expected to have less importance than the spectral broadening due to the initial electron beam energy chirp described in [8]. From the bandwidth values given in Table 3 we see that the relative spectral broadening due to the CSR is only about 30% for the initially chirped electron beam. The wavelength shift due to the CSR is still observed; however, it is comparable to the bandwidth in this case.

CONCLUSION

We have investigated how the dynamic energy profile of the electron beam in the EEHG seeding section can affect the output FEL radiation spectrum. We considered the energy profile of the electron beam at the exit of the first chicane with and without CSR (in free space) effects in the chicane. In addition, we simulated the spectral shape of the FEL radiation by the beam in both cases. From comparing the two cases, we have concluded that taking CSR into account can significantly affect the EEHG-based FEL radiation spectrum. The effect of CSR on the spectrum in the presence of a linear energy chirp in the electron beam was investigated as well. We concluded that the effect of the CSR-induced energy modulation in the presence of the chirp is significantly less critical. Future work will extend this work to include internal beam scattering and the effects of chamber walls.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Gauss Centre for Supercomputing e.V. (www.gauss-centre.eu) for funding this project by providing computing time through the John von Neumann Institute for Computing (NIC) on the GCS Supercomputer JUWELS [11] at Jülich Supercomputing Centre (JSC). The work is supported by BMBF within “05K2019-STAR” project. The authors also acknowledge the funding through the Lund-Hamburg “IFELD” collaboration.

REFERENCES

[1] G. Stupakov, “Using the Beam-Echo Effect for Generation of Short-Wavelength Radiation,” *Phys. Rev. Lett.*, vol. 102, p. 074801, 2009. `doi:10.1103/PhysRevLett.102.074801`

[2] E. Hemsing *et al.*, “Echo-enabled harmonics up to the 75th order from precisely tailored electron beams,” *Nat. Photonics*, vol. 10, pp. 512–515, 2016. `doi:10.1038/nphoton.2016.101`

[3] P. Rebernik Ribič *et al.*, “Coherent soft X-ray pulses from an echo-enabled harmonic generation free-electron laser,”

Nat. Photonics, vol. 13, pp. 555–561, 2019. `doi:10.1038/s41566-019-0427-1`

[4] L. Schaper *et al.*, “Flexible and Coherent Soft X-ray Pulses at High Repetition Rate: Current Research and Perspectives,” *Appl. Sci.*, vol. 11, p. 9729, 2021. `doi:10.3390/app11209729`

[5] S. Reiche, “GENESIS 1.3: a fully 3D time-dependent FEL simulation code,” *Nucl. Instr.*, vol. 429, pp. 243-248, 1999. `doi:10.1016/S0168-9002(99)00114-X`

[6] D. Samoilenko, W. Hillert, F. Pannek, P. Niknejadi, G. Paraskaki, F. Curbis, M. Pop, S. Werin, “Discussion on CSR Instability in EEHG Simulation”, in *Proc. 12th Int. Particle Accelerator Conf. (IPAC’21)*, Campinas, SP, Brazil, May. 2021, pp. 1622-1624. `doi:10.18429/JACoW-IPAC2021-TUPAB103`

[7] M. Borland, “elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation,” in *Proc. 6th International Computational Accelerator Physics Conference (ICAP’2000)*, September 11-14, 2000, Darmstadt, Germany LS-287, `doi:10.2172/761286`

[8] E. Hemsing, B. Garcia, Z. Huang, T. Raubenheimer, D. Xiang, “Sensitivity of echo enabled harmonic generation to sinusoidal electron beam energy structure,” *Phys. Rev. Accel. Beams*, vol. 20, p. 060702, 2017. `doi:1103/PhysRevAccelBeams.20.060702`

[9] M. Borland, “Simple method for particle tracking with coherent synchrotron radiation,” *Phys. Rev. ST Accel. Beams*, vol. 4, p. 070701, 2001. `doi:10.1103/PhysRevSTAB.4.070701`

[10] M. Borland, “User’s Manual for elegant,” `https://ops.aps.anl.gov/manuals/elegant_latest/elegant.html`

[11] D. Alvarez, “JUWELS Cluster and Booster: Exascale Pathfinder with Modular Supercomputing Architecture at Juelich Supercomputing Centre,” *Journal of large-scale research facilities*, vol. 7, p. A183, 2021. `doi:10.17815/jlsrf-7-183`