

SIMULATION STUDIES ON THE SELF-SEEDING OPTION AT FLASH*

V. Miltchev[†], J. Rossbach, Hamburg University, 22761 Hamburg, Germany
B. Faatz, R. Treusch, DESY, 22603 Hamburg, Germany.

Abstract

In order to improve the temporal coherence of the radiation generated by the Free-electron LASer in Hamburg (FLASH), a two-stage seeding scheme [1] is presently under construction. It consists of two undulator stages separated by a magnetic chicane and a monochromator. In this contribution we investigate various configurations of the electron optics of the seeding set-up. The optimization of the lattice in the first (seeding) stage and the parameters of the magnetic chicane will be discussed. Simulation results for the performance of the second (seeded) stage of the FEL will be presented.

INTRODUCTION

The basic setup of the self-seeding option [1, 2] is illustrated in Fig. 1. It consists of two undulator stages separated by a magnetic chicane and a monochromator. The first undulator operates as a SASE FEL in the linear regime. After it, the electrons are separated from the SASE radiation. The

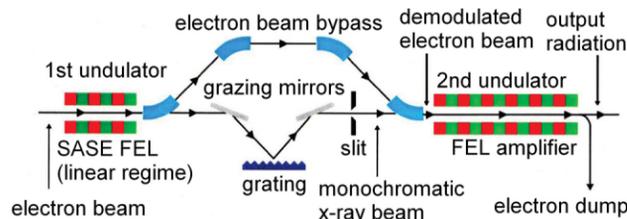


Figure 1: Schematic layout of the self-seeding setup.

electron beam passes through the magnetic bypass, that is used to remove the longitudinal charge density modulation (micro bunching). The radiation pulse is spectrally filtered in a high resolution grating monochromator [3] and afterwards is superimposed with the electron beam at the entrance of the second undulator. Thus the monochromatic photon beam serves as a coherent radiation seed, which is amplified up to saturation in the second undulator. The seeding increases the spectral brilliance by about a factor of 100, i.e. the output power of the seeded FEL is concentrated in a single line which is about a hundred times narrower than the spectrum of the conventional SASE FEL. The concept of the self-seeding has the advantage that it is independent of any external radiation source and the seed is naturally synchronized with the electron bunch. An additional advantage is that the seeding wavelength is continuously tunable. The monochromator optics, to be installed

at FLASH, is designed for operation in the 6-60 nm range [2]. It is important to note, that the gain in the first undulator section is essential for the effective operation of the self-seeded FEL. The output power level should be sufficiently low (about two-three orders of magnitude below saturation) in order to preserve the energy spread and the emittance of the electron beam. On the other hand the power of the seed, obtained from the first stage, should be much higher than the power of the shot noise in the second undulator.

ELECTRON OPTICS

Undulator stages

The undulator stages for the self-seeding option are subdivided into segments of about 4.5 m length. The first and the second undulator consist of three and six such segments respectively. A separated focusing system for the undulator stages is used at FLASH [4]. The focusing is accomplished by quadrupole doublets placed in-between two neighbouring undulator segments. The main feature of such focusing scheme, relevant to the implementation of the self-seeding, is the variable quadrupole strength. The total length of the first undulator (about 14.5 m) is optimized for operation at a wavelength in the order of 6 nm. The minimum average β -function for this case is about 4.5 m. As mentioned above, the power gain in the first undulator is crucial for the performance of the self-seeded FEL. Therefore, in order to compensate the scaling of the gain with the wavelength, one can vary the quadrupoles strength i.e. tune the average β -function accordingly.

Electron bypass

The bypass has to meet various requirements in order to ensure the proper operation of the self-seeding. The most essential of them are summarized in the following:

- Generation of an additional path length for the electrons, which is equal to the extra path length of the photons in the monochromator.
- Reduction of the micro bunching generated by the SASE process along the first undulator section. The micro bunching after the bypass is reduced by a factor of $\exp\left(-\frac{1}{2}\sigma_\delta^2 R_{56}^2 k_L^2\right)$ [5]. Here σ_δ is the fractional momentum spread, R_{56} is the momentum compaction factor of the bypass and k_L the radiation wavenumber.
- Adjustment of the electron optics to the optics of the two undulator sections for radiation wavelengths in the range 6-60 nm.

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[†] velizar.miltchev@desy.de

- Correction of the first and second order dispersion, minimization of the degradation of beam quality due to coherent synchrotron radiation effects.

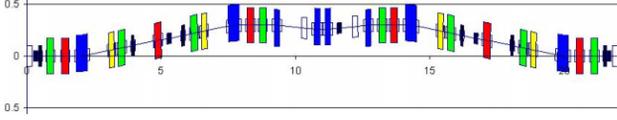


Figure 2: Final magnet layout of the electron bypass for the Seeding Option (side view). *black*: steerer, *blue*: dipole, *green*: quadrupole, vertical focusing, *red*: quadrupole, horizontal focusing, *yellow*: sextupole.

In contrast to the simplified scheme shown in Fig. 1, the final design of the electron bypass optics [2], as sketched in Fig. 2, consists of a total 37 magnets.

SIMULATION TECHNIQUES

The simulation studies presented in this paper divide into two groups: studies on the performance of the self-seeded FEL and investigations of the impact of the coherent synchrotron radiation (CSR), emitted in the electron bypass, on the output brilliance.

Performance of the self-seeded FEL

The performance of the self-seeded FEL has been simulated with the 3-D time dependent FEL-code GENESIS [6]. The simulation is split into two runs - the first undulator operating as a SASE FEL and then simulation of the electron bypass together with the second undulator. The complete particle distribution at the end of the first undulator is extracted and then is used in the next simulation step. The electron bypass is implemented in GENESIS by the means of a 6×6 transfer matrix. In the second step, the particle distribution extracted from the first part of the simulation is transformed with the help of the bypass matrix and then tracked through the second undulator section. A certain wavelength λ_{seed} and average power P_{seed} is assumed for the external seed, which should be obtained at the output of the monochromator beamline. In the presented studies the two extreme cases $\lambda_{seed} \approx 6$ nm and $\lambda_{seed} \approx 60$ nm are considered. It is helpful to remind that the seed power should fulfill the requirement $P_{seed} \gg P_{shot}$, where P_{shot} is the effective shot noise power. Since $P_{shot} \leq 100$ W, a seed of $P_{seed} \approx 10$ kW has been assumed in all cases. The code ELEGANT [7] has been used for the calculations of the electron optics, to find the electron beam matching conditions and for the calculation of the transfer matrix of the bypass. The electron beam parameters, which have been assumed in the simulations, are summarized in Table 1

Studies on CSR effects

These investigations follow a similar scheme as the one described above. However, in order to include CSR ef-

Table 1: Nominal electron beam parameters for operation at 6 nm

Energy, E_0	1000 MeV
Peak current, I_0	2500 A
rms energy spread	0.2 MeV
Normalized rms emittance, ϵ_n	2 mm mrad
rms bunch length, σ_z	50 μ m

fects in the numerical calculations, the bypass has been simulated together with the first undulator section with the ELEGANT code. The program incorporates 1-D CSR algorithm [8] for dipoles and drift spaces. The produced particle distribution file is afterwards analyzed and converted into averaged slice information, which is used by GENESIS to simulate the interaction between the electrons and the radiation field along the second undulator section. In order to quantify the influence of the emitted synchrotron radiation, the described procedure has been repeated twice. Once including the CSR effects and second time with the CSR algorithm switched off. The average spectral flux has been considered as a figure of merit to compare the radiation quality for the two cases.

SELF-SEEDING PERFORMANCE

As it is pointed out in [4], one of the main advantages of the separate focusing is that the number of quadrupoles in-between the undulator segments can be reduced, what

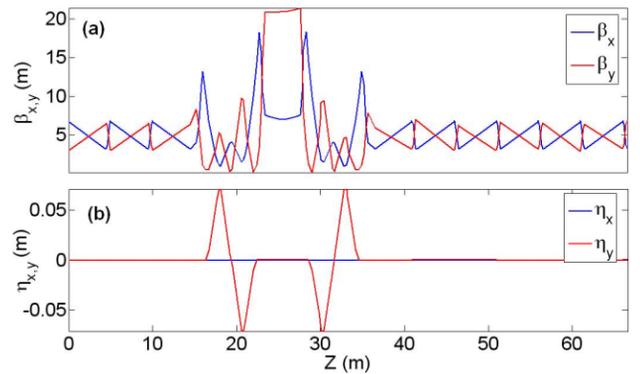


Figure 3: β -function (a) and dispersion (b) along the self-seeding electron beamline.

results however in an increase of the minimum average beta function $\langle \beta \rangle$. For the case of electron energy $E_0=1000$ MeV, corresponding to a wavelength $\lambda \approx 6$ nm, an average β -function of about 4.5 m is used. As shown in Fig.3, the design of the electron optics allows operation with the same $\langle \beta \rangle$ at the both sides of the magnetic chicane. For such setup the first stage works in the linear regime (see Fig. 4) with an average power of the output radiation of about 5 MW. Again in Fig. 4 it is shown the evolution of the micro bunching along the undulator. The kinks around $Z=10$ m and $Z=5$ m (less pronounced) are due

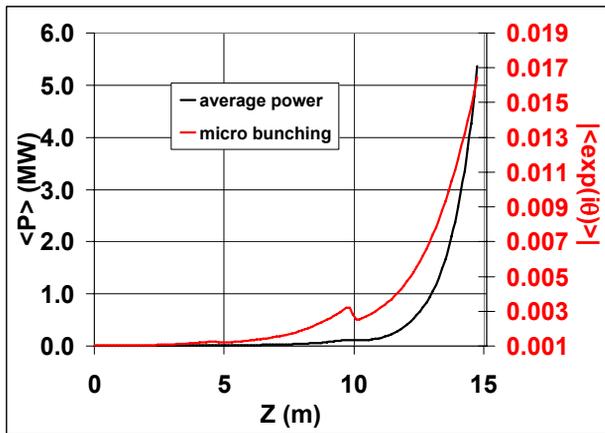


Figure 4: Average radiation power and micro bunching (right axis) along the first undulator.

to debunching taking place in the quadrupole doublet intersections [4]. Figure 5 shows the radiation power and

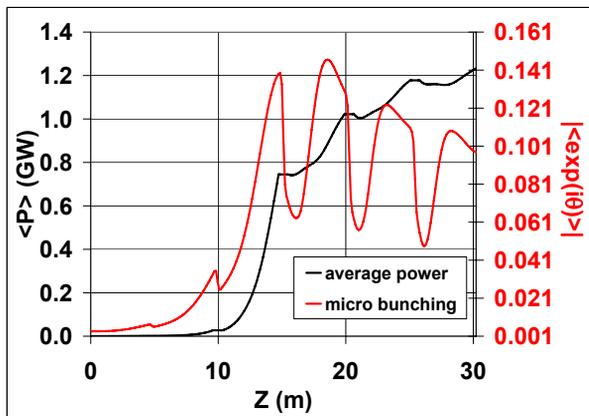


Figure 5: Radiation power and micro bunching (right axis) along the second undulator. Seeding wavelength $\lambda_{seed} \approx 6.31$ nm.

bunching as a function of the length of the second undulator. A comparison between the graphs in Fig.4 and Fig.5 demonstrates that the momentum compaction factor of the bypass $R_{56} \approx 0.73$ mm is sufficient for the reduction of the micro bunching induced in the first undulator.

For operation at electron beam energy of 325 MeV, corresponding to a resonant wavelength of about 60 nm, one has to consider modifications in the electron optics of the first undulator section and the chicane. These changes are necessary because of the scaling of the FEL gain with the wavelength. The electron optics designed for 6 nm, with $\langle \beta \rangle \approx 4.5$ m (see Fig.3), provides saturation length in the order of 20 m for SASE mode. For the 60 nm case, however, the saturation length is only about 9 m, which is significantly shorter than the first undulator (14.5 m) and therefore not acceptable from the point of view of the self-seeding option. One possible solution, as confirmed by

simulations, is to increase $\langle \beta \rangle$ in the first stage to a value in the order of 25 m, corresponding to the desired low gain of about three orders of magnitude below saturation.

Variation of the seeding wavelength

The monochromator design gives the possibility for variation of the wavelength of the seed across the full bandwidth of the FEL amplifier. Therefore it is interesting to investigate the influence of the seeding wavelength on the power and the spectrum of the output radiation. In Fig. 6 the spectral flux along the second undulator is presented for various seeding wavelengths. The simulations show a maximum at $Z \approx 15.5$ m for $\lambda_{seed} = 6.305$ nm. One has to

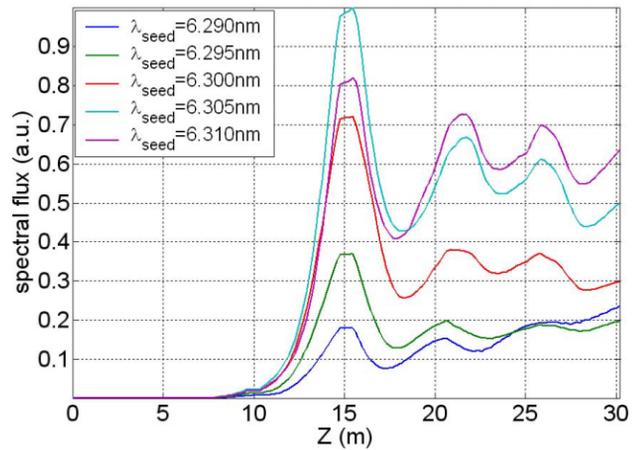


Figure 6: Spectral flux as a function of the undulator length for different λ_{seed} and constant seeding power.

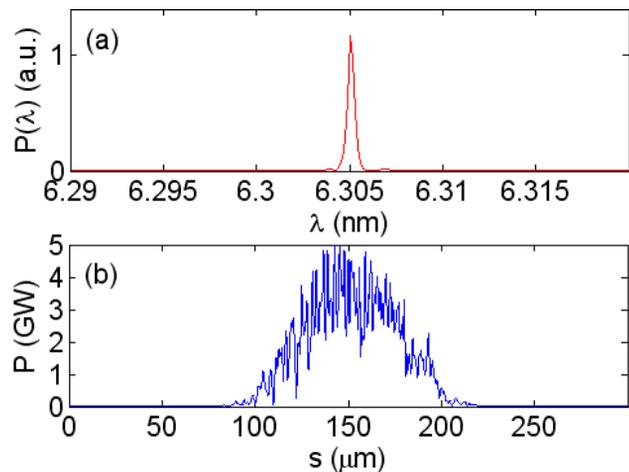


Figure 7: Spectrum (a) and power along the radiation pulse (b) in the second (seeded) section at $Z=15.5$ m.

mention that the position of the maximum of the spectral flux is related to the onset of the nonlinear regime (see Fig. 5). Further increase of the output power is coupled with a spectral broadening and in consequence with reduction of the spectral flux. As studied in [9], the length of the second

undulator can be optimized in order to compensate the large fluctuations of the seed intensity after the monochromator. The simulation results plotted in Fig. 7 demonstrate the effect of the self-seeding on the spectrum and the power of the output radiation. The two graphs in Fig. 7 correspond to the maximum of the spectral flux.

CSR effects

The electron bunches entering the magnetic chicane are of rms length $\sigma_z \approx 50 \mu\text{m}$ and high peak current $I_0 \approx 2.5 \text{ kA}$. Therefore, despite the small bending angle $\theta = 3^\circ$,

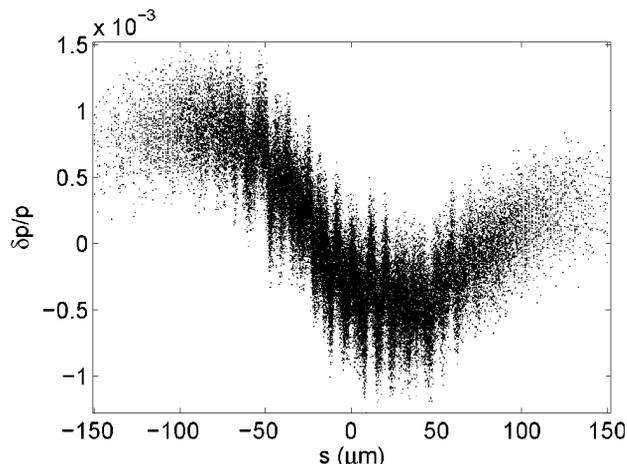


Figure 8: Distortion of the longitudinal phase space due to synchrotron radiation produced in the bypass dipoles.

the coherent component of synchrotron radiation, generated in the bypass dipoles, can be significant and might dilute the electron beam quality. Simulations of the CSR-induced emittance dilution have been made using the ELEGANT code, which result in a projected emittance growth in the order of a percent. The slice emittance is, however, almost unchanged. A much more significant impact on the longitudinal phase space is expected, as presented in Fig.8. The total relative energy spread has increased from 2×10^{-4} up to about 5×10^{-4} . The growth of the energy spread is due to the correlation in the longitudinal phase space created by the synchrotron radiation, but on the other hand the slice energy spread is practically unaltered. The increased energy spread will drive more particles outside of the amplifier bandwidth and as a result one anticipates a reduction of the gain. Moreover the correlation in the phase space produces side bands in the spectrum or in other words spectral broadening. Fig. 9 shows that there is about a factor of two decrease in spectral flux due to CSR effects. It is important to note that we have considered the worst case scenario i.e. the bypass optics and electron beam parameters have not been tuned to mitigate the impact of CSR.

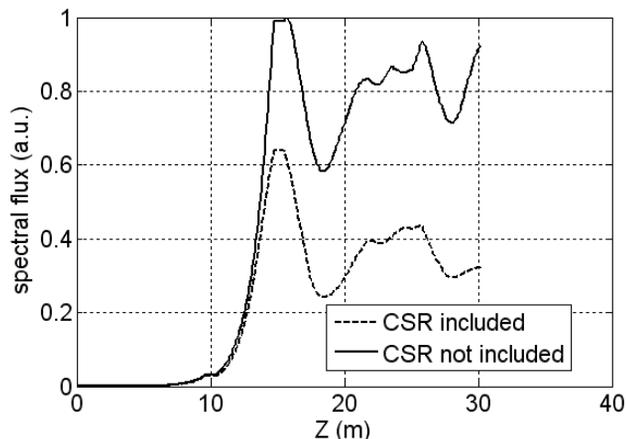


Figure 9: Demonstration of the impact of CSR effects - the spectral flux as a function of the undulator length.

CONCLUSIONS AND OUTLOOK

The operation of the two stage FEL has been studied, taking into account all the details in the design of the electron optics. Simulation results demonstrate a feasible operation in a wide range of electron energies and wavelengths. Investigated is also the possibility to fine tune the seeding wavelength, accomplished using the monochromator beamline settings. The impact of the coherent synchrotron radiation emitted in the bypass dipoles was studied. The simulations predict about a factor of two reduction of the spectral flux due to CSR. Further studies including wave front propagation through the monochromator beamline are ongoing [10]. As a next step the tolerances of the electron beam parameters, the accuracy of magnets alignment and the impact of the magnetic field errors will be analyzed.

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