OPTIMIZATION OF FEL PERFORMANCE BY DISPERSION-BASED BEAM-TILT CORRECTION

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Abstract

In Free Electron Lasers (FEL) the beam quality is of crucial importance for the radiation power. A transverse centroid misalignment of longitudinal slices in an electron bunch reduces the effective overlap between radiation field and electron bunch. This leads to a reduced bunching and decreased FEL performance.

The dominant sources of slice misalignments in FELs are the coherent synchrotron radiation within bunch compressors as well as transverse wake fields in the accelerating cavities. This is of particular importance for over-compression, which is required for one of the key operation modes for the SwissFEL under construction at the Paul Scherrer Institute in Switzerland.

The slice centroid shift can be corrected using multi-pole magnets in dispersive sections, e.g. the bunch compressors. First and second order corrections are achieved by pairs of sextupole and quadrupole magnets in the horizontal plane while skew quadrupoles correct to first order in the vertical plane.

INTRODUCTION

An FEL strives to have a relative bandwidth of the photon energies of the order of 10^{-4}. For specific applications like powder diffraction, Bragg imaging, or single-shot absorption spectroscopy much larger bandwidths are desirable to increase the chance of hitting resonances [1, 2]. A special configuration of the FEL under construction at PSI Switzerland, SwissFEL [3], will yield a bandwidth of up to 3% at 1 Å to fulfill these needs. In the following we refer to it as the large-bandwidth mode of SwissFEL.

This mode uses a high energy chirp along the bunch to increase the photon bandwidth. The longitudinal wakefields [4] originating in the cavities of the last linac and an over-compression in the final bunch compressor (BC) to revert the sign of the incoming energy correlation create the needed chirp. Because of over-compression coherent synchrotron radiation (CSR) considerably deteriorates the transverse profile by introducing beam distortion in the bending plane.

A beam slice misalignment reduces the overlap between the electron beam and its radiation field. This leads to a reduction of SASE performance in the offset regions. CSR, being a major contributor to the beam tilt, is of concern at small bunch lengths within the bending magnets. Therefore correction of the tilt is of special importance for the large-bandwidth mode of SwissFEL utilizing over-compression.

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This work implements an alternative description of the beam tilt [5] and quantifies its effect on the lasing through genesis [6] simulations. In addition we address the induced orbit and bunch length jitter.

THEORY

This section describes the beam tilt and how to manipulate it. In this work x stands for both transverse planes and z the longitudinal direction. The Taylor approximation of the beam tilt μ is:

$$\tilde{x}(z) = x + \sum_{i=1}^{n} \mu_i \left(z^i - \langle z^i \rangle \right), \tag{1}$$

$$\tilde{x}'(z) = x' + \sum_{i=1}^{n} \mu_i' \left(z^i - \langle z^i \rangle \right), \tag{2}$$

where n corresponds to the highest order to be considered. Misaligned beam parameters are denoted by a tilde. This description has the benefit of adjustable abstraction without losing analytical correctness if n reaches infinity.

This work uses the statistical emittance (ε) defined as:

$$\varepsilon_x^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2 . \tag{3}$$

The parameter x' denotes the momentum normalized by the total momentum. The beam tilt μ alters the emittance as follows:

$$\tilde{\varepsilon} = \varepsilon \sqrt{1 + M_n + M_n^*} , \tag{4}$$

where M corresponds to the pure and M^* to the mixing term. They are both expressed through

$$M_n = \frac{1}{\varepsilon_x} \sum_{i,j=1}^{n} \left(\beta_x \mu_i' \mu_j' + \gamma_x \mu_i \mu_j - 2\alpha_x \mu_i \mu_j' \right) Z_{i,j} , \tag{5}$$

$$M_n^* = \frac{1}{\varepsilon_x^2} \sum_{i,j,k,l=1}^{n} \left(\mu_i \mu_j \mu_k' \mu_l' - \mu_i \mu_j' \mu_k \mu_l' \right) Z_{i,j} Z_{k,l} , \tag{6}$$

where α,β,γ are the Twiss parameters and $Z_{i,j}$ is the reduced mean, defined as:

$$Z_{i,j} = \langle z^{i+j} \rangle - \langle z^i \rangle \langle z^j \rangle . \tag{7}$$

For a linear longitudinal phase-space correlation, considering μ up to only first-order ($n = 1$), M^* vanishes and M simplifies to

$$M_1 = \frac{\varepsilon_z \beta_z}{\varepsilon_x} \left(\mu_1'^2 \beta_x + \mu_1^2 \gamma_x + 2\mu_1 \mu_1' \alpha_x \right), \tag{8}$$

where ε_z corresponds to the longitudinal emittance and β_z to the longitudinal beta function.

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The beam tilt leads to a deviation of slice and projected parameters like emittance and mismatch parameter, therefore making it harder to operate the machine in places where the slice beam parameters cannot be measured. More importantly the beam tilt reduces the FEL power, specifically at the tails of the bunch. The slices are offset to the undulator axes and undergo betatron oscillations, thereby reducing the overlap between radiation and electrons. In addition does μ changes the optics making it more difficult to match the beam (core) due to the mismatch along the bunch. A series of genesis simulations demonstrate this behaviour (figure 1. The far-field is used as performance benchmarks, since it

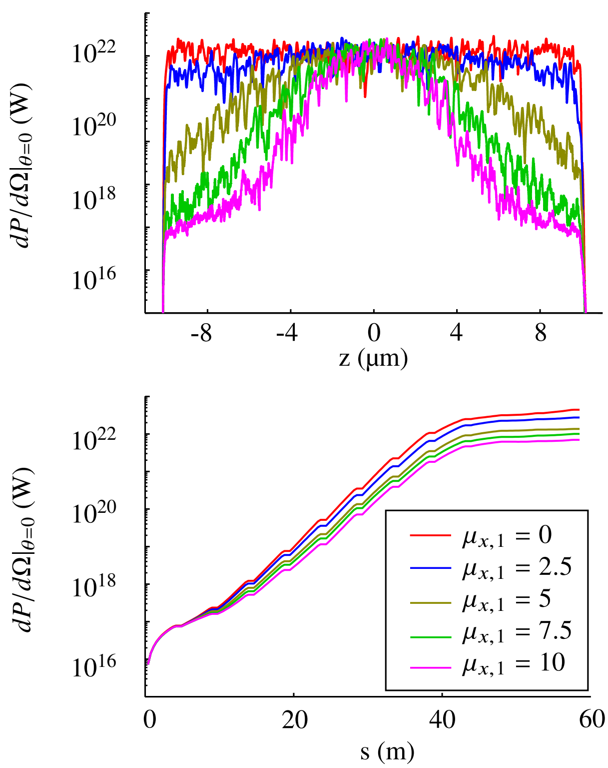

Figure 1: Scan of $\mu_{x,1}$. The bottom graph shows the radiation growth along the SwissFEL undulator line whereas the top one represents a snapshot along the FEL pulse at the end of the undulator line.

possess a clearer start up signal and lower contribution by higher transverse modes at the power level of spontaneous radiation.

CORRECTION ALGORITHM

Static fields cannot act differently on electrons in a bunch, as long as the electrons have the same orbit. This changes in a dispersive section (η) with a strictly monotonic chirp along the bunch: here a given longitudinal position is mapped uniquely to a transverse position. A superposition of multipole fields allows acting independently on these positions.

In the following we distinguish between lattice and beam dispersion and tilt. The lattice parameters only depend on the beam line and do not take into account any self interaction. The beam parameters on the other hand are derived from the higher-order moments in the beam independent from their source.

For a linear longitudinal phase space and an energy chirp with $|\alpha_z| \gg 0$, μ and η are directly linked by:

$$\mu_i \approx \left(\frac{-\alpha_z}{\beta_z}\right)^i \eta_i\,, \tag{9}$$

where μ_i and η_i correspond to the Taylor approximation terms of the beam tilt or the dispersion, respectively.

The condition of a strictly monotonic chirp is fulfilled at the bunch compressors. Therefore by adjusting the lattice dispersion the beam tilt can be controlled by changing the beam dispersion. The existing energy chirp vanishes in the subsequent C-band linac due to longitudinal wakefields thereby unlinking lattice dispersion and beam tilt because $\alpha_z \approx 0$. Any applied correction will now be independent of magnetic multipoles as long as there is no energy correlation along the bunch. The leaking lattice dispersion is then independent from any corrected bunch dispersion. This means that the orbit of the bunch is still energy dependent but the phase space coverage in momentum and space is not.

Due to the large lattice dispersion at the correction locations weak corrector magnet strengths are sufficient to achieve the desired manipulation of η. This has the benefit of only marginally disturbing the optics.

CORRECTION IMPLEMENTATION

To measure the beam tilt μ the beam is streaked by a transverse deflecting cavity or by a (skew) quadrupole magnet within the BC. Since the longitudinal phase space at the BC is strictly monotonic both methods are equivalent. The tilt in momentum (μ') is reconstructed by measuring μ for several phase advances.

The perturbation matrix is measured using all available corrector magnets as knobs and measurements of μ, R_{56} and chromaticity. To suppress low impact contributions the matrix elements not mentioned in table 1 are forced to zero. By measuring several phase advances it is then possible to reconstruct μ as well as μ' at any given point. The implementation of the correction algorithm is discussed in more detail in [5].

Table 1: Pairing for Perturbation Response Matrix (not mentioned elements are set to zero to increase stability)

Knobs	Quad	Skew quad	Sextupole	Dipole
Penalties	$\mu_{1,x}$	$\mu_{1,y}$	$\mu_{2,x}$	R_{56}
	$\mu_{1,x'}$	$\mu_{1,y'}$	$\mu_{2,x'}$	
			Chromaticity	

SIMULATIONS

The simulations of this work focus on the large bandwidth mode of SwissFEL [3] utilizing over-compression. The

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resulting strong CSR kick makes the need for the correction most critical for this mode.

For correction both BC's in SwissFEL are equipped with a pair of (skew) quadrupole and sextupole magnets. These 12 corrector magnets are used to correct for the beam tilt while keeping chromaticity at bay. The change in R_{56} is then adjusted by the bending angle of the bunch compressors.

Elegant [7] simulations up to the undulator entrance were done followed by genesis simulations to quantify the gain in FEL power. Figure 2 shows the increase in power through the applied correction. The correction increases the power

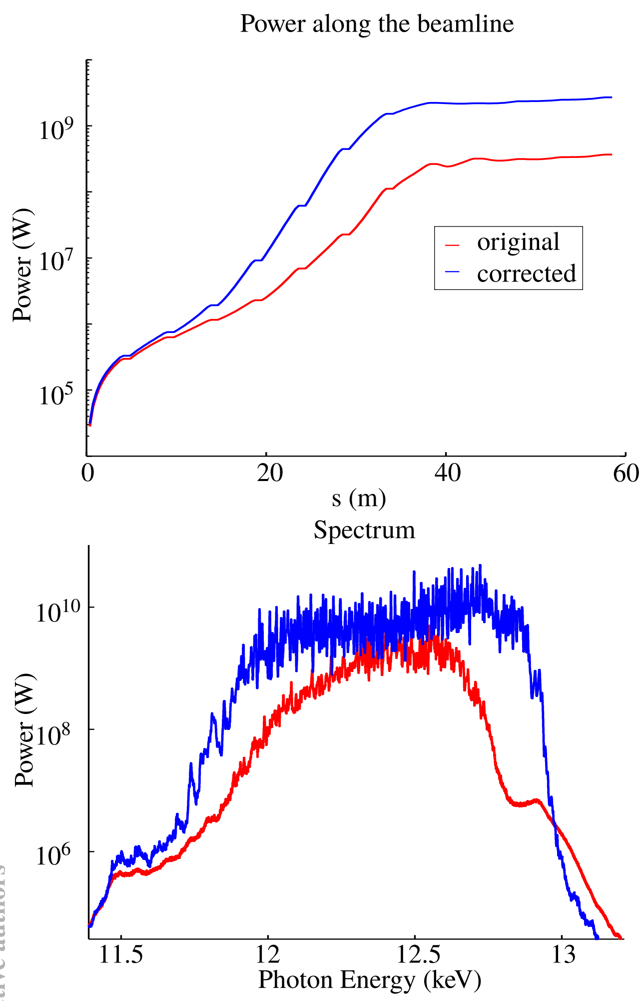

Figure 2: Genesis simulations for the SwissFEL large bandwidth mode at $\lambda_{\text{photons}} = 1$ Å. The top picture shows the FEL power for the corrected and the uncorrected case. The resulting increase in FEL power is about one order of magnitude. Uncorrected configuration exhibits narrower spectra, counteracting the goal of the large bandwidth mode.

by one order of magnitude at saturation. Furthermore the correction increases the photon bandwidth, which is a critical parameter for the large-bandwidth mode. This is mainly because the tails are now contributing stronger in the overall SASE process. This leads to a broadening of the spectrum due to the strong energy chirp which is translated into a frequency chirp of the FEL pulse.

JITTER

The leakage of lattice dispersion out of the bunch compressors leads to energy induced orbit jitter. An orbit offset within the undulator leads to subsequent orbit oscillations reducing FEL power.

Since it is not possible to correct the leakage of this lattice dispersion without introducing new bunch dispersion, it is important to investigate the sensitivity to energy jitter.

In addition to the orbit jitter T_{566} is enlarged, which in case of an energy jitter $\Delta\delta$ leads to an altered $\tilde{R}_{56}$ of

$$\tilde{R}_{56} = R_{56} + 2T_{566}\Delta\delta\,, \tag{10}$$

considering up to second order matrix elements [8].

The SwissFEL tolerance of an acceptable beam orbit jitter is 10% of its rms beam size in momentum and space. The bunch length jitter is tolerable up to 10% of its length. The jitter study shows that the orbit as well as the bunch length jitter stay well within their respective tolerance levels. Figure 3 shows their distributions by jittering the RF klystrons at their respective tolerance values in phase and amplitude [3].

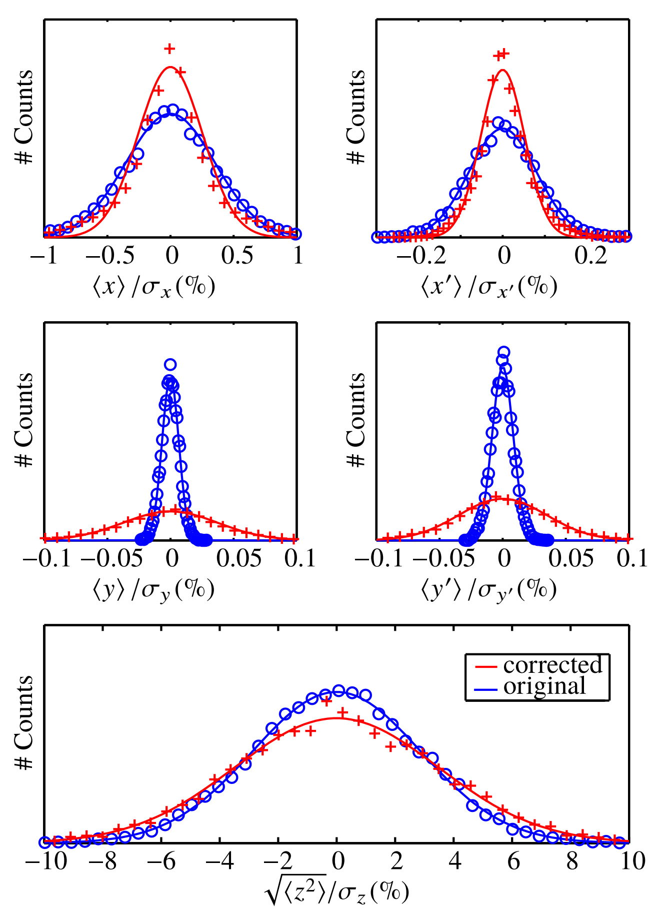

Figure 3: 10'000 Jitter runs for both corrected and uncorrected cases. The additional orbit jitter originating from the leaking dispersion is minimal and is well within tolerances of SwissFEL. The points correspond to the actual data points and the lines correspond to Gaussian fits.

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The gun laser jitter was studied by varying the charge of the electron bunch and proved to be of no significance.

Other sources of orbit jitter [3] in the machine are stronger than the contribution from the leaked lattice dispersion. The same holds true for the bunch length jitter. The increase in orbit and bunch length jitter stays within the acceptable limits and does therefore not restrict the applied correction.

DISCUSSION

We have proposed a correction scheme for slice misalignment and validated it in simulation and with measurements. In simulations we see an tremendous increase of nearly one order of magnitude in FEL power for a strongly misaligned beam. The correction is of particular importance for the large-bandwidth mode because of the strong CSR kick due to over-compression and the spectral broadening. The experiment delivered a proof-of-principle of feasibility of the introduced method as presented in [5].

The proposed iterative correction method implementing a perturbation matrix is applicable in practice because it respects tolerance values in terms of mismatch and jitter of the machine.

Concerns about the energy induced orbit and bunch-length jitter are addressed and are well below the tolerance level for the expected jitter budget for SwissFEL.

We conclude that the presented method is feasible to correct μ and make the large-bandwidth mode viable for SwissFEL.

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