TOLERANCE STUDIES FOR THE HARD X-RAY BEAMLINE OF SWISSFEL

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Abstract

The planned X-ray facility at the Paul Scherrer Institut will span a wavelength range between 1 Ångstroem and 7 nm, distributed over 2 beamlines. The design aims for a compact layout with low electron beam energies and short undulator periods for the hard X-ray beamline. The resulting tolerances are the most stringent for the operation at the shortest wavelength of 1 Å. The tolerance study, presented here, distinguish the error sources between those of components within the undulator beam line (e.g. undulator field errors) and jitter in the electron beam parameters. The latter can be used as the figure of merits for defining the tolerance budget of the injector and linac.

INTRODUCTION

With the recent progress towards shorter wavelength of Free-electron Lasers down to Angstrom radiation [1], the demands on the quality of the electron beam and undulator system becomes more stringent to provide sufficient and reliable operation of the SASE FELs. This applies also for the SwissFEL project [2] at the Paul Scherrer Institut in Switzerland. The hard X-ray beamline [3] between 1 and 7 Ångstrom is optimized for a compact design with short undulator periods and narrow gaps, which increases the sensitivity towards alignment and field quality. To guarantee the success of the project the sensitivities of the FEL have to be studied and compared to the tolerances, which are achievable. This allows to optimize the design process and to mitigate error sources, which have a strong impact on the FEL process.

ERROR SOURCES

This document covers only the error sources, which occur within the undulator beam line, or affects the FEL on a shot-shot basis in terms of electron beam position jitters. This excludes all explicit errors in the linac, which still can have a severe impact on the FEL performance but can be expressed as jitters of the electron beam parameters at the undulator entrance. These jitters are forming one class of error sources, which have a dynamic impact on the machine. Due to the nature of being a jitter, beam parameters can fluctuate from shot-shot, which has a direct but deterministic impact on the FEL performance. Therefore an error study only has to scan over a given amplitude of the jitter and analyze the dependence on the FEL performance. The other class of errors is given by the components of the undulator beamline such as alignment errors or module detuning. In difference to electron beam jitter a tolerance value has to be obtained from different seeds of the random number generator to get a better picture of the impact on the FEL performance. In some cases it can happen that some errors actually have a beneficial effect. An example is if the last module before saturation is slightly detuned so that the additional phase slippage between electron bunching and radiation field pushes the electrons towards a stronger emission and energy losses. Any of the errors can affect the FEL in two ways: reduced transverse overlap and longitudinal synchronization.

For SwissFEL, operating at 1 Ångstrom, the gain-guided optical mode of the radiation field is smaller than the electron beam. If the electron beam is steered away the radiation field cannot follow immediately. The characteristic length of this guiding is the gain length. The FEL process can recover by rebuilding the radiation field by the already induced micro-bunching. This takes about one gain length but requires that the electron beam is not steered away from its current direction of motion.

The second impact is a disruption of the longitudinal velocity and thus the synchronization of the bunching phase with the co-propagating radiation field. This is caused either by the detuning of the undulator modules, phase mismatches in the phase shifter between the undulator modules, or the shift in the electron energy due to wakefields and emission of incoherent undulator radiation. However any change in the resonance condition can be matched by changing the undulator along the beam line as long as the change is deterministic and depends only on the position within the undulator and not within the bunch. This is actually necessary to compensate for the losses due to undulator wake fields or spontaneous radiation.

ERROR SENSITIVITY AND TOLERANCE BUDGET

There are various sources of errors, which affect the FEL performance. To investigate the required tolerances for the FEL performance it is important to first identify the sources and second study the sensitivity on the FEL performance. As a measure for the sensitivity is the drop of the output power of the FEL below an acceptable level, e.g. by fitting a Gaussian dependence to the drop in the FEL pulse energy to the magnitude of an error source. This is a reasonable approach because for different samples of the error distri-

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bution (e.g. quadrupole offsets) but same rms magnitude the FEL output can vary.

The various error sources for the hard X-ray beamline are: undulator field errors, undulator alignment, quadrupole field errors, quadrupole alignment, initial beam offset, initial beam angle, and beta mismatch.

The undulator field errors have been simplified, which are treated as a variation between the modules but kept constant over each individual module. We assume a planar configuration of the Aramis undulator with no dependence of the magnetic field in the horizontal direction. Therefore a misalignment in the horizontal plane should not have any impact on the FEL performance. Also the misalignment does not include tilted or rotated undulator modules, nor additional error sources which only apply for the soft X-ray FELs (phase shifter, energy and arrival jitter for the seeding configuration).

Under the assumption that the error sources x_j are independent of each other the total FEL performances is the product of the various Gauss-functions with the different sensitivities σ_j for each error source: $P = P_0 \Pi_j \exp(-x_j^2/2\sigma_j^2)$, where P_0 is the FEL output energy under ideal condition, excluding errors. Based on the sensitivities, which are derived from the simulation, a given tolerance budget can be defined. Assuming that a given tolerance is a fraction of the sensitivity ($x_j = a_j\sigma_j$) the 1-sigma tolerance budget is defined as $\sum_j a_j^2 = 1$. Uneven weights allow balancing out more sensitive error sources against less sensitive sources. If a given tolerance is on the 10% level of the sensitivity it will only contribute by 1% to the total error budget. In the case of Aramis, where 7 errors have been identify, and giving the same budget to all error sources than the tolerance is about 30% of the sensitivity (note that quadrupole alignment, initial offset and angle as well as beta-mismatch has to be counted for both transverse directions).

SIMULATION APPROACH AND FIGURE OF MERITS

The major obstacle for studying undulator error in steady-state models is a possible shift in the resonance condition, which can have a strong impact on the FEL performance if only one frequency is considered. This problem is avoided if a time-dependent SASE simulation is performed, though with the drawback of the statistical fluctuation in the average power. Therefore the dependence of the FEL signal on the error source has to be larger than the intrinsic fluctuation of the FEL. For Aramis at 1 Ångstrom, the intrinsic fluctuation is of the order of 10%.

As described in the first section all the error sources can affect the FEL performance in two ways: longitudinal and transverse overlap. Therefore it is fruitful to express all error sources in terms of these two effects. For the transverse overlap it is the straightness of the electron trajectory. Note that this is not necessarily the undulator axis but rather the axis defined by the injection of the electron beam itself. Therefore a line is fitted to the orbit to minimize the rms deviation from this reference orbit. As such the rms off-axis beam wander is defined as:

$$\sigma_x = \frac{1}{L_u}\sqrt{\int_0^{L_u} (x(z) - az - b)^2 dz},$$

where a and b are the constant of the line fit to the trajectory. The equivalent definition for the longitudinal motion is the phase shake, the rms fluctuation of the ponderomotive phase with respect to a co-propagating plane wave. Note, that a slight detuning in the electron energy can compensate a linear drift. Therefore any linear change in the phase is taken out of equation by subtracting a linear phase drift. The phase shake becomes:

$$\sigma_\theta = \frac{1}{L_u}\sqrt{\int_0^{L_u} (\Delta\theta(z) - cz - d)^2 dz},$$

where the 'phase wander' $\Delta\theta$ is given by the detuning of the undulator field and the transverse centroid motion:

$$\Delta\theta(z) = -k\int_0^z \left(\frac{K^2}{2\gamma^2}\frac{\Delta K(z)}{K} + \frac{\Delta p_x^2 + \Delta p_y^2}{2p_z^2}\right) dz.$$

The quantities for the off-axis wander and phase shake can easily be derived from the simulations and correlated against the FEL performance.

INDIVIDUAL ERROR SOURCES

Undulator Detuning and Misalignment

For this study the undulator field is varied for each of the 13 modules in the Aramis beamline. Within a module the undulator field is kept constant and individual variation over a single module is not considered. A collective detuning of the module would add up in a phase slippage with respect to the resonance wave. A sinusoidal variation along the module with the same amplitude ΔK would yield a reduced phase shake because half-way through the module the relative velocity of the electron to the resonant wavefront turns around and the electrons falls back.

The correlation between detuning and phase shake has the proportionality constant of 10.48 in units of rms variation in percent. For the given rms phase shake the dependence on the FEL output power is shown in Fig. 1. A Gaussian fit yields a sensitivity (aka the rms width of the Gaussian) of 0.7653 rad. Expressed in terms of undulator error it is 0.073%, which is comparable to the FEL parameter. However the overall set of runs has still a strong residual fluctuation overlaid upon the Gaussian dependence. For some sets it actually ended up in an enhancement of the FEL performance. This is the result of somehow emulating effects of tapering or optical klystrons, which both enhance the efficiency of the FEL.

Undulator misalignment has two impacts on the electron beam. First the natural focusing of the undulator acts

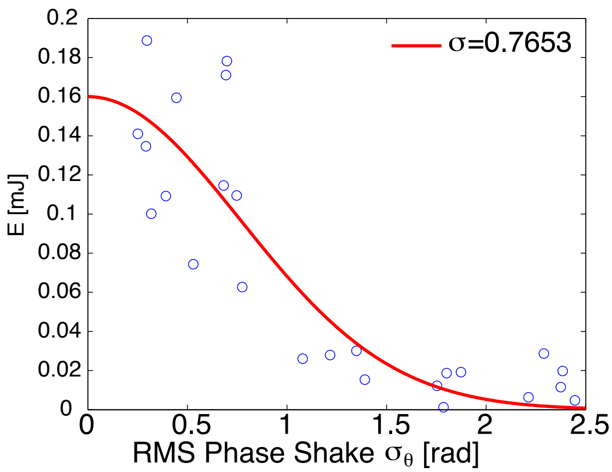

Figure 1: Sensitivity of the FEL energy at the saturation point of the undisturbed FEL performance for the phase shake caused by undulator module detuning of the Aramis beam line at one Ångstrom.

like a misaligned quadrupole and steers the beam transversely. Because the effective focal strength drops with larger energy this effect is negligible for X-ray FELs such as Aramis. The other effect is the detuning of the undulator field due to the transverse dependence of the undulator field strength, which is given by $K = K_0(1+k_x^2x^2+k_y^2y^2)$, where the values of the roll-off parameters k_x and k_y depend on the explicit design of the undulator. For the ideal case of a planar undulator with infinite wide pole faces the roll-off values are $k_x = 0$ and $k_y = k_u$. It is a very good approximation for the Aramis undulator while for APPLE-type undulators the values can be significantly larger even in the planar configuration of the undulator. The correlation of the offset errors to the resulting phase shake is quadratic with the constant 141.7 mm^{-2} for the quadratic term. The fitted Gaussian has the rms width is 0.9751 rad. This value is reasonable similar to the fitting results for the module detuning, indicating that the effective detuning of the module by its offset is the main reason for the degradation. Expressed in alignment errors the resulting sensitivity is 83 μm rms.

Quadrupole Field Variation and Misalignment

A variation in the quadrupole field strength results in a non-matched electron beam and a variation in the electron beam size along the undulator. However the overall focusing strength is relatively weak because the optimized beta-function is 15 m as compared to the total undulator length of 70 m. As expected the dependence on the field variation is weak with a sensitivity of 20.96 % rms.

Quadrupole misalignment disrupts the FEL performance by steering the electron beam transversely resulting in a shift in the resonance condition because the projected longitudinal velocity is reduced, secondly, the separation of the electron beam from the radiation field, and, thirdly, a reduced emission in the forward emission. The last cause arises from the fact that though the trajectory has changed the orientation of the micro-bunches has not. With respect to the new direction, which still fulfills the resonance condition, the micro bunches seems to be rotated and the emission in the direction of propagation is reduced. This is typical method to disable the FEL performance by strongly steering the electron beam for a measurement of the FEL power along the undulator [4]. The minimum angle, where the FEL is turned off, is given by the transverse size of the micro bunches and the resonant wavelength: $\theta > \lambda/\sigma_r$. For the Aramis beam line the angle is about 10^{-5} rad, which results in an offset of 40 μm over one undulator module. Under this angle the electron beam would be well separated from the radiation field and for the following discussion it can be assumed that the main effect is the reduced overlap between the electron beam and radiation field.

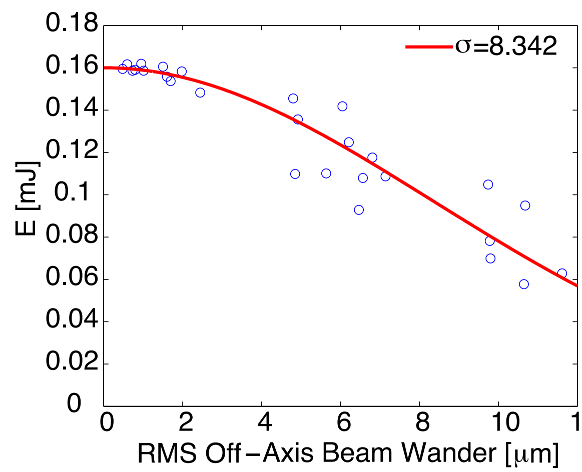

Figure 2: Sensitivity of the FEL energy at the saturation point of the undisturbed FEL performance for the beam wander caused by quadrupole misalignment of the Aramis beam line at one Ångstrom.

The dependence of the FEL energy on the beam wander is shown in Fig. 2 and has a fitting parameter of 8.342 μm for the Gaussian distribution. That corresponds to a sensitivity on quadrupole misalignment of 4.6 μm RMS. It has to be mentioned that it isn't quite a realistic assumption that the quadrupole misalignment can be described by a simple random distribution because a beam-based alignment will actually minimize the rms beam wander directly by shifting quadrupole position to minimize the dispersion in the undulator beamline. However similar studies for the LCLS beam line have shown that the rms beam wander is a suitable parameter to describe the effect on the FEL performance [5].

Electron Injection Jitter and Beta-Mismatch

Electron beam injection errors are directly transferred into a beam wander around the optimal trajectory. It can be expected that the same sensitivity is achieved as for quadrupole misalignment. This is indeed verified by a sensitivity of 8.277 μm for the beam wander, which is almost identical to 8.342 μm for the quadrupole misalignment and well within the error of the parameters in the Gaussian fit.

Similar to an injection error of the electron beam centroid the electron beam envelope can be mismatched to the lattice of the undulator beam line. A mismatch results in a variation of the electron beam size with the periodicity of the betatron period, which is about 90 m and thus longer than the undulator length. On the characteristic scale of the FEL performance, the gain length, this effect is less pronounced, however it can locally yield too small beta function, which then enhances the axial velocity spread through the emittance [6]. Unlike the other error sources it is not possible to simply fit a Gaussian to the FEL energy at saturation. The dependence is shown in Fig. 3 and has a clear asymmetry around the matched value of the matched beta-function β_0. Nevertheless, on a logarithmic scale for the beta-mismatch the dependence is Gaussian and the fitting value is 0.385 if the base-10 logarithm is used. This corresponds roughly to a factor 2.5 around the match beta-function. With a value of $\beta_0 = 15$ m, values for the beta function between 6 m and 35 m are within the sensitivity of the beta-mismatch.

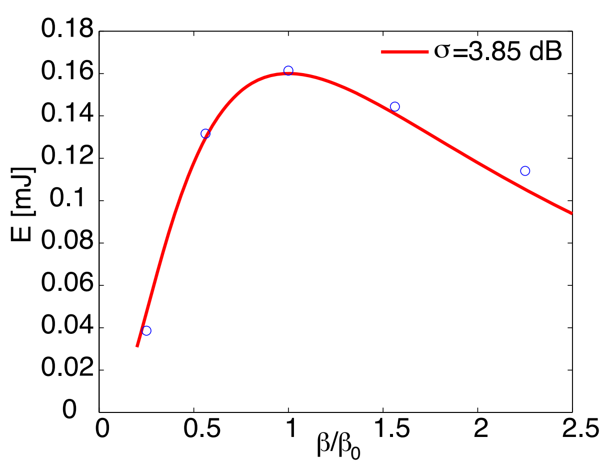

Figure 3: Sensitivity of the FEL energy at the saturation point of the undisturbed FEL performance for the beta-mismatch of the Aramis beam line at one Ångstrom.

CONCLUSION

The sensitivities for errors in the Aramis undulator beam line are shown in Tab. 1. From all the sources the quadrupole field and the beta-mismatch can be considered as weak error sources, where it shouldn't be too difficult to achieve a performance much better than the sensitivity. This allows us to take them out of the error budget by weighting them by a weak factor (e.g. 0.1) and thus contributing to the total error budged with less than 5%. On the other hand the quadrupole alignment and the injection errors are the most demanding tolerances but still reasonable. To set-up an error budget, input is needed from other groups about what can be expected to be achieved in reality. If the expect performance is better than the sensitivity, those error sources can be weighted less and thus allows other error sources to have larger tolerances. Finally, all error sources, which describe the undulator beam line itself, are stationary, where the FEL performance is affected in the same way for each shot (unlike the electron beam jitter). Also the sensitivity was derived by the FEL power at a fixed point. Just by adding more undulator length can partially compensate a drop by one e-folding length. With a given module length of 4 m an additional module would be sufficient to reach saturation. A coarse estimate indicates a drop in the effective FEL parameter and thus FEL output energy by less than 10% though the point of saturation is shifted backwards.

Table 1: Sensitivities of various error sources for the Aramis beamline

Error	RMS Sensitivity
Undulator Detuning	0.073%
Undulator Misalignment	83 μm
Quadrupole Field Errors	20.96%
Quadrupole Misalignment	4.6 μm
Injection Offset	11.7 μm
Injection Angle	0.78 μrad
Beta-Mismatch	3.85 dB

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