STUDY OF BEAM BASED ALIGNMENT AND ORBIT FEEDBACK FOR SWISSFEL

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Abstract

Transverse beam trajectory control is of great importance for SwissFEL as the lasing strategy is based on a relatively low energy and low emittance beam compared with other X-FEL facilities. This paper discusses the beam based alignment (BBA) of SwissFEL, taking into account BBA tolerances and beam position monitor performance. The undulator BBA is challenged by rather tight tolerances. An orbit feedback together with a suitable technique to passively stabilize the beam will be discussed with reference to some available data on dynamic disturbances, namely the ground motion and related beam jitter for SwissFEL and its test injector that is currently being commissioned.

INTRODUCTION

Transverse beam trajectory control is of great importance for SwissFEL as the lasing strategy is based on a relatively low energy and low emittance beam compared with other X-FEL facilities, thus aiming at reasonable construction cost and size of the facility. The normalized emittance is 0.18/0.43 mm.mrad for 10/200 pC operation modes, respectively, and the beam energy is 2.1/5.8 GeV for the soft/hard X-ray beam lines [1].

The performance of beam diagnostics, especially the beam position monitor (BPM) noise, is relevant to beam based alignment (BBA) and was therefore taken into account in BBA simulations. Since the undulator BBA is challenged by rather tight tolerances, we need not only sufficiently good diagnostics but also an elaborated alignment procedure.

The tight tolerance of the undulator BBA corresponds to tight tolerances on the beam stability at the entrance of undulator. In addition to an active feedback system, we investigate means to localize dynamic disturbances to be removed or mitigated in order to detect and eliminate perturbation sources as much as possible. The impact of two dynamic disturbances, namely the ground motion and the initial beam jitter are also discussed.

BEAM BASED ALIGNMENT

The main goal of BBA in the linac is to establish a beam trajectory where transverse emittances are well preserved. Emittance dilution occurs mostly due to spurious dispersion over accelerating structures, thus a tolerance on linac dispersion is specified. In the undulator section, the trajectory must be aligned very precisely, to a few μm level, which corresponds to ~0.1σ of the beam size. Major tolerances are summarized in Table 1.

Table 1: Major BBA Tolerances for 200 pC Operation Mode (where sensitivity is specified, tolerance must be several times smaller depending on the total error budget).

Parameters	Values	Remarks
Linac dispersion	1~2 mm	Emittance preservation
Orbit straightness in undulator	10 μm RMS	Sensitivity. FEL power ~40% down
Undulator positioning	125 μm	Sensitivity in ver. plane for planner undulator

Survey based mechanical alignment precision in short range (10~20 m) is expected to be 50 μm RMS. Relatively large alignment errors above 50~100 μm will be detected beam-based and then corrected by mechanical realignment in the tunnel, to reduce corrector strengths and offsets in the BPMs for better performance.

Three steering algorithms, namely dispersion free steering (DFS) [2], ballistic alignment (BA) [3] and "threading" where the beam is steered to go through BPM centres have been simulated for the SwissFEL main linac lattice. In simulations, the BPM reading error of 3 μm RMS is assumed. However, this number is not a requirement of BBA but the expected performance of the main linac BPMs. Figure 1 shows typical simulation results.

Although threading will result in larger residual dispersion of a few mm which is comparable to the tolerance, this quick and easy algorithm is still expected to be useful in the early stage of commissioning before applying more advanced BBA techniques. Figure 1 (a) implies the initial alignment precision of 50 μm RMS is good enough to obtain an acceptable orbit perturbation for first machine commissioning.

When using DFS based BBA (the main option for SwissFEL), the achievable residual dispersion depends on BPM reading errors but not on alignment errors since difference orbits for various beam momenta are measured. The dispersion measurement error is then of the order of the BPM reading error divided by the relative change in beam momentum (or magnetic field equivalently). It will be improved to some extent by averaging measurements over many shots. Even with only 20% momentum change, the residual dispersion will be an order of magnitude smaller than the tolerance when using low noise BPMs.

The performance of BA depends on both BPM reading and alignment errors, but the former is expected to be much smaller. We could stay within the tolerance with BA as well partly because the SwissFEL linac is relatively short.

It is worth mentioning that an additional steering can be applied in which the dispersion is varied without disturbing the trajectory and vice versa. This is realized by localized orbit bumps over quadrupoles which generate angular dispersion since the bumped orbit is dispersive. A similar technique using orbit bumps over linac cells is described in [4]. In summary, the BBA for the SwissFEL linac is expected to be fairly non-critical.

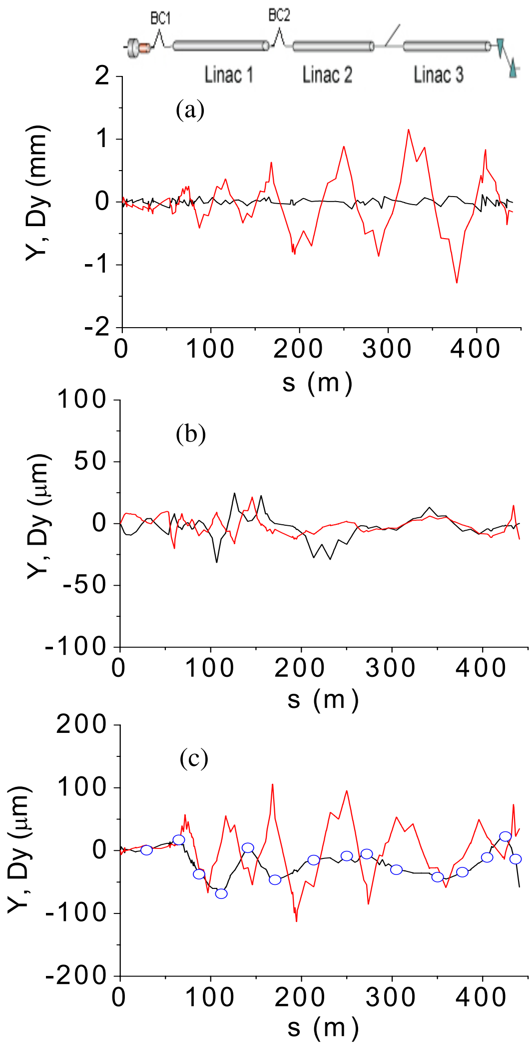

Figure 1: Typical simulation results for various steering algorithms. The black and the red line show trajectory and dispersion, respectively. (a) Threading: BPM alignment error 50 μm RMS, (b) DFS: Dispersion measurement error 15 μm RMS, BPM noise 3 μm RMS, energy variation 20%, (c) BA: Pivot BPM (indicated with blue circle) alignment error 75 μm max, BPM reading error 3 μm RMS.

The LCLS has established an undulator alignment scheme based on DFS together with precise undulator-quadrupole pre-alignment [5]. This scheme is also the baseline of the SwissFEL undulator BBA. However, we need to modify the scheme since a mechanical analysis predicts that a quadrupole on the undulator girder could be displaced about 5 μm when the undulator gap is changed, while the gap is fixed in the LCLS undulator. Therefore quadrupoles as well as BPMs will be placed on a dedicated girder in between the undulator cells.

Furthermore we are investigating to use, as a replacement of beam finder wires, small quadrupoles called “alignment quads” which are only powered during the BBA procedure to determine if the beam goes through its magnetic centre. If the beam is not centred with respect to the alignment quad, the beam position in a downstream BPM is displaced when turning it on. To avoid remanent fields from the alignment quads, we are investigating the use of air-core magnets.

A schematic layout of the undulator section is shown in Fig. 2, and the procedure of undulator BBA is to:

- Open all undulator gaps
- Align quadrupoles mounted on motorized 2D movers with DFS
- Record the BPM readings for the aligned electron beam
- Close and align undulators one by one such that the electron beam position does not change in a downstream BPM by turning on and off alignment quads, reproducing the recorded BPM readings (correcting small kicks due to undulator residual first integrals)
- Fine tuning, k-tapering and phase matching

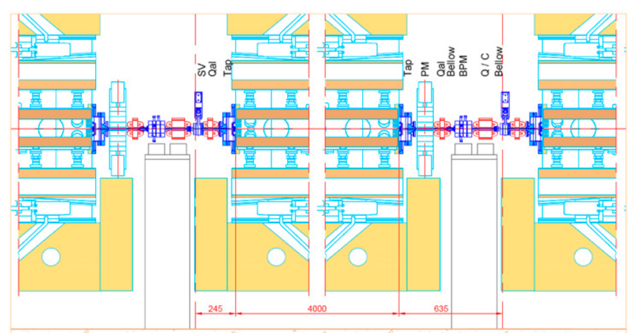

Figure 2: Schematic layout of the undulator section.

The tolerance on orbit straightness is tight and will be achieved with DFS using sufficiently precise BPMs. We estimated the orbit straightness to be 1~2 μm RMS when the BPM reading error is 1 μm RMS. In general, the undulator positioning tolerance is considered to be rather uncritical and can be achieved either with alignment quads or beam finder wires.

Alternatively, the undulator section could be aligned based on the photon beam. The idea is that the orbit straightness of the electron beam is ensured when the quadrupole magnets are aligned such that photon beams generated at each undulator point to the centre of a photon beam monitor downstream as schematically shown in Fig.3. Due to the large opening angle of the spontaneous undulator radiation, a better photon beam position measurement would be possible by selecting a frequency component above the maximum resonant frequency with a monochromator. The alternative procedure of undulator BBA could be as follows:

- Open all undulator gaps but the first one
- Align the undulator and quadrupole such that the photon beam points to the centre of photon beam monitor (the residual first integral is included here)
- Record beam position at the BPM right after the undulator
- Repeat the above steps until the last undulator is aligned.
- Close the undulator gaps one by one to confirm the reproduction of the recorded positions, otherwise slightly steer the electron beam
- Fine tuning, k-tapering and phase matching

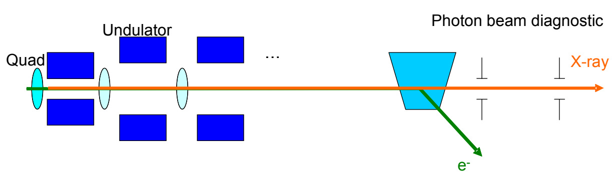

Figure 3: Illustration for the photon beam based alignment (alignment of the first undulator).

FEEDBACK AND BEAM STABILIZATION

The sensitivity on the undulator orbit straightness given in Table 1 corresponds to a beam stability tolerance of a few µm at the entrance of undulator section. This requires several low noise BPMs (~1 µm RMS) in the undulators and their matching section. For the injector and main linac, the beam stability requirements with respect to emittance dilution are moderate, although higher stability is desired to minimize perturbations generated in the linac which affect the undulator electron and beam stability. The BPM noise for injector and linac is specified as <10 µm RMS, although smaller values would be beneficial e.g. for perturbation source detection or energy measurement in the bunch compressors.

The required beam stability can be realized with a combination of active feedback, adaptive feed-forward, and source-suppression of perturbations. We intend to use a fast trajectory feedback (FOFB) that allows one to compute the setting of all actuators in the feedback loop (corrector magnets, but also other machine components) at the 100Hz bunch repetition rate. Cascading of multiple feedback loops will also be supported, thus avoiding crosstalk issues that typically occur when employing several independent local feedbacks.

Running the feedback at the bunch repetition rate of 100 Hz allows one to maximize its zero dB point frequency. The latency of the system in term of digital signal processing can easily be achieved with standard technology. The corrector magnets should be laminated and equipped with a thin steel beam pipe to suppress eddy currents.

The baseline algorithm to compute the corrector strengths will be matrix pseudo-inversion using singular value decomposition (SVD), offering significant flexibility such as noise filtering with eigen-value cut, or the choice of different number of sensors and actuators as required for optimal performance of the machine. The computed values will be sent to corrector power supplies and other actuators using e.g. a standard PID controller.

Although the feedback frequency is 100 Hz, the zero dB point frequency will be around 10 Hz. Thus it is important to stabilize the beam passively with open loop. BPMs with sufficient resolution and a suitable distribution along the machine should enable us to localize and then mitigate any harmful perturbations by beam measurements, using spectral analysis of BPM data from all BPMs over a few hundred shots [6].

After we stabilize the beam, the closed FOFB loop will be optimized based on real-time frequency spectra of BPM readings in the undulator section, revealing if a particular frequency component of fluctuation is random, stationary or quasi-stationary. If the fluctuation contains relatively strong (quasi-)stationary frequency component(s) even after the passive stabilization, it is reasonable to apply a feed-forward.

The impact of ground motion has been evaluated based on available measurement data. Ground motion measurements at the future SwissFEL site show a dominant ~10 Hz component, in addition to common low frequency motion, due to the adjacent industrial activity as main source. The FOFB is not effective to the motion because of the frequency close to the zero dB point. Figure 4 shows a power spectrum density (PSD) measured on the surface. The ground motion will be attenuated by the tunnel building [7] and enhanced by girder and support structures. Assuming that the attenuation/enhancement factor is not far from unity, the beam motion due to 2~20 Hz ground motion has been simulated using the measured motion on the surface to evaluate whether the ground motion is critical or not. The result showed several 100 nm beam fluctuation, which is acceptable.

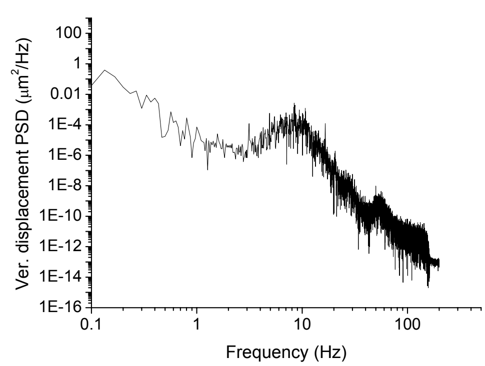

Figure 4: Measured displacement PSD showing a peak around 10 Hz.

The SwissFEL injector test facility is currently under commissioning. First measurements with its resonant stripline BPMs show good initial beam stability. Although the gun in the injector will be replaced by a new PSI RF gun in SwissFEL, injector construction know-how has been acquired, and similar or better beam jitter may be realized in SwissFEL. Further measurements are scheduled.

BPM SYSTEM

The SwissFEL undulators will be equipped with dual-resonator cavity RF BPMs that apply mode-suppressing couplers in order to reach the desired (sub-)micron level drift and resolution, with a required beam charge range of at least 10-200 pC. A similar BPM type is presently being developed by a collaboration of PSI and DESY for the European XFEL [8], with the goal to adapt the design to the requirements of the SwissFEL (lower bunch charge, shorter bunch spacing, etc.).

For SwissFEL injector and main linac, the more relaxed drift and resolution requirements suggest the use of either cavity BPMs or e.g. resonant striplines that should both be able to reach the noise of <10 μm RMS for the injector (38 mm inner pipe diameter) and <5 μm RMS for the main linac (16 mm inner diameter) down to 10 pC with comparably cost-efficient pickup and electronics designs. The SwissFEL test injector that is presently being progressively installed and commissioned allows investigation of both BPM types, with resonant striplines as robust standard BPMs [9] based on existing PSI technology, and a cavity BPM R&D test section at the end of the injector.

CONCLUSION

Transverse trajectory control was studied for SwissFEL where emittance preservation and beam stabilization is highly important.

The BBA for the SwissFEL main linac was simulated and found to be non-critical with respect to emittance preservation. In contrast, tolerances in the undulators are rather tight. The undulator BBA will be based on a modified LCLS scheme, using high-resolution BPMs. An alternative/complementary scheme based on photon BPMs is also under investigation.

SwissFEL will employ active trajectory control using a combination of fast feedback (FOFB) and adaptive feed-forward. The FOFB will apply SVD matrix inversion and e.g. PID control. Source suppression of perturbations is important to achieve the necessary beam stability. Spectral and spatial analysis of BPM data will allow one to localize any remaining perturbations. First measurements at the future SwissFEL building site indicate rather low perturbation levels for ground motion, and first measurements at the SwissFEL test injector show good initial beam stability. Other important disturbances such as CSR kicks in bunch compressors will be studied in the future.

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