RESPONSE MATRIX OF LONGITUDINAL INSTRUMENTATION IN SwissFEL

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Abstract

Several sources of jitter and drift affect the longitudinal phase space dynamics of SwissFEL. To evaluate how drifts can be identified and corrected through appropriate diagnostics and beam-based feedbacks, the response matrix of possible longitudinal diagnostics on laser and RF stability is modeled. To this intent, photocathode laser intensity, laser arrival time, RF phases and RF amplitudes are individually varied in an ELEGANT model, and the expected response of on-line diagnostics on the simulated bunches is evaluated. By comparing the slope of the response to the expected resolution of the instrumentation, suitable monitors can be selected for a feedback.

INTRODUCTION

To meet the growing demand for ultra-short X-ray pulses, Paul Scherrer Institut is currently designing the SwissFEL free electron laser [1]. One key objective of SwissFEL is to provide users with sub-picosecond pulses of excellent stability [2]. The design consists of a photocathode electron gun, an injector using both S- and X-band radio frequency (RF) accelerating cavities (at frequencies of 3 and 12 GHz, respectively), to produce a linear longitudinal phase space distribution, followed by a magnetic chicane as a first bunch compressor (BC1). To control the slice energy spread, a laser heater is foreseen in the middle of the injector. The main accelerator uses C-band accelerating cavities at a frequency of 5.7 GHz and contains a second bunch compressor (BC2).

The performance of the FEL depends on transverse and longitudinal electron beam stability, and beam-based feedbacks are foreseen to compensate for drifts in these parameters. The transverse stability is ensured by a rigid mechanical design, supplemented by a high-resolution beam position monitor system [3] that will be used for beam-based orbit feedbacks [4]. This is necessary both to minimize transverse wakefields in the accelerating structures, and to achieve a straight orbit in the undulators.

Of equal importance is the longitudinal stability. The dependence of the longitudinal phase space at the undulator entrance on key parameters such as the RF phases and amplitudes, the bunch charge, the arrival time and the bunch compressor magnet stability has been studied [5]. Here, a simulation was set up where the parameters were varied one by one within a range spanning a few time the expected stability. Within this range, the response of the accelerator is linear.

It was shown that stringent longitudinal stability requirements have to be met to ensure a reliable user operation, in particular for the short pulse operating mode. A considerable effort will therefore be made to improve the intrinsic stability of the RF systems. A comprehensive longitudinal instrumentation will provide the signals to a global feedback system, to ensure that drifts are properly compensated. Such beam-based system are also implemented at the LCLS [6] and at FLASH [7].

Ideally, one would like to have independent beam-based measurements of the parameters that affect the longitudinal phase space distribution. This would require a full characterization of the longitudinal phase space after each accelerator element, which is neither technically nor financially feasible. Instead, a suite of longitudinal instrumentation has been designed to measure phase space parameters at certain key points in the SwissFEL accelerator, mainly around the bunch compressors (Figure 1).

It has to be noted that the present paper describes a work in progress, which will be extended to include further parameters and diagnostics that will be installed in SwissFEL, and ultimately compared to beam-based measurements.

INSTRUMENTATION FOR THE LONGITUDINAL PHASE SPACE

SwissFEL will be equipped with a comprehensive longitudinal instrumentation (Table 1). Bunch charge will be measured with integrating current transformers and the monopole cavities of the BPMs [3]. Bunch arrival time will be measured with electro-optical modulators that sample the fields derived from the electron bunch with a pulsed reference laser [8]. Beam position monitors in dispersive sections measure the mean particle energy, while an energy distribution will be measured with synchrotron light cameras [9]. Bunch length will be measured with electro-optical monitors [10] and coherent diffraction or synchrotron radiation monitors [11].

DIAGNOSTICS RESPONSE TO KEY ACCELERATOR PARAMETERS

Certain dependencies of measured values on the parameters of the accelerator can be derived analytically. For example, the orbit in the bunch compressors is a function of the particle energy, which can easily be calculated form RF amplitudes and phases.

Other dependencies are less obvious: the total energy of a CDR pulse is proportional to the square of the bunch

ISBN 978-3-95450-117-5

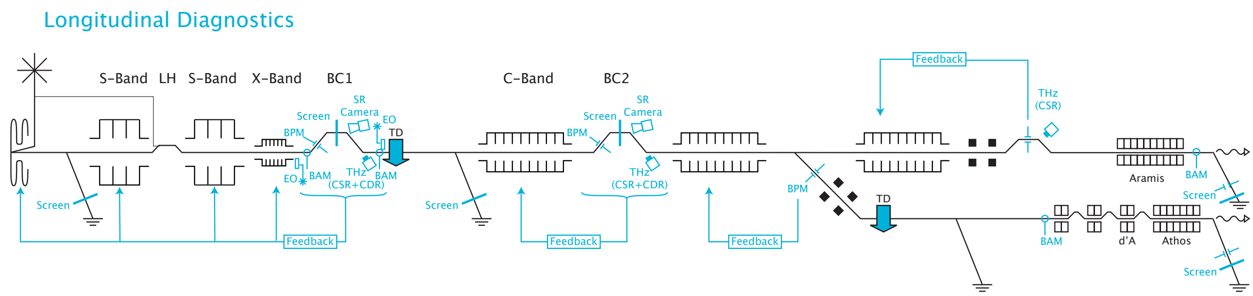

Figure 1: Overview of the longitudinal diagnostics foreseen for SwissFEL. BAM: bunch arrival monitor, BC1: first bunch compressor, BC2: second bunch compressor, BPM: beam position monitor, EO: electro-optical monitor, LH: laser heater, TD: transverse deflecting cavity.

Table 1: Instrumentation that has been Simulated in this Study

Symbol	Quantity	Expected Resolution
BPM Q	Bunch charge	0.4 pC
BAM t_0	Arrival time at the first BAM	10 fs
BPM x BC1	Horizontal BPM in BC1	3 μm
SRC σ_x BC1	Size, as measured by SR camera in BC1	30 μm
CDR LW BC1	CDR after BC1, integrated from 300 GHz to 1 THz	13dB
CDR MW BC1	CDR after BC1, from 1 to 3 THz	13dB
CDR SW BC1	CDR after BC1, from 3 to 10 THz	13dB
BAM Δt BC1	Transit time through BC1	14 fs
EO FW ABC1	EO monitor after BC1	30 fs

charge; however, the bunch charge also influences longitudinal wake fields, which affect the bunch length. As we will see later, the dependence of total CDR energy on bunch charge is indeed negative for variations around the nominal operating parameters of SwissFEL.

To obtain a more complete picture of the response of diagnostics to changes of key accelerator parameters affecting the longitudinal phase space, a numerical study has been performed. In the present paper, the accelerator section from the beginning of the laser heater to the end of the diagnostics section after BC1 will be presented. Table 2 lists the parameters relevant to this section, Table 1 lists the values measured by the instrumentation.

The simulation was performed in the following steps.

1. The SwissFEL lattice[1] from the start of the laser heater to the diagnostics after BC2 was simulated using ELEGANT. The calculation is started with a particle distribution derived from and ASTRA simulation of the gun and the first half of the injector. 100’000 particles are tracked through the accelerator.

2. For each parameter, error studies in 25 runs relative to a fiducial run are performed, using a range of a few times the expected shot-to-shot stability of the systems.

3. The full particle distribution in phase space is dumped at each diagnostics element.

4. The instrumentation is simulated with MATLAB. For each diagnostics element, one or a few numerical values are extracted:

   - For the arrival time and position, the arithmetic mean of all particles is used.
   - For the synchrotron radiation camera, a two-dimensional histogram as image is generated, and Gaussian curves are fitted to the projections.
   - For CDR diagnostics, the current profile is generated by binning the particles; from this, the power spectrum is calculated and integrated over four wavelength bands
   - For the electro-optical monitors, the current profile is generated, from this the response of the electro-optical crystal is derived, from which the effect on the spectrum of the laser is calculated. Finally, the bunch length information is extracted.

5. The response of each value on each parameter is plotted and found to be linear within this range. Therefore, simultaneous variations of all parameters can be represented as a linear combination of the individual variations, and methods from Linear Algebra can be applied to search for patterns in the response.

[1] For the present study, the baseline design as of June 2011 is used, for the nominal operating parameters in the 200 pC mode.

ISBN 978-3-95450-117-5

Table 2: Key Parameters Affecting the Longitudinal Phase Space that have been Varied in this Study. Please note that the information on expected stability is only used in this paper to normalize the response matrix, and is sometimes not based on measurements but on guesses or extrapolations of existing data.

Symbol	Quantity	Expected Stability	Variation Window
Q	Bunch charge	1%	± 2 pC
t_0	Arrival time at the start of the laser heater	30 fs	± 100 fs
E_0	Energy at the start of the laser heater	0.01%	± 0.05%
Φ_S	S-band phase of the modules after the laser heater	0.015°	± 0.1°
A_S	S-band voltage of the modules after the laser heater	0.012%	± 0.1%
Φ_X	X-band phase	0.06°	± 0.1°
A_X	X-band voltage	0.012%	± 0.09%

6. From a linear fit, a slope is obtained. This is the response R_{ij} of diagnostics i to parameter j, i.e. the Jacobian matrix of the system.

7. These responses have different orders of magnitude, and different units. They thus have to be normalized.

   - The parameter changes were normalized to the expected rms stabilities.
   - The response was normalized to the expected rms resolution for a single-shot measurement.

   Thus, we obtain dimension-less response values. Values larger than one correspond to effects that can be detected reliably in a single shot. However, we do not expect such fast drifts. By averaging 100 bunches over one second, we can make use of response matrix elements larger than 0.1.

In Table 3, the normalized response matrix for the section between the beginning of the laser heater and the end of the first bunch compressor diagnostics is given.

Table 3: Response Matrix of the Measured Values as a Function of Key Accelerator Parameters. The values have been normalized by the expected stability of the varied parameters and by the expected resolution of the diagnostics.

	Q	t_0	E_0	Φ_S	A_S	Φ_X	A_X
BPM Q	5.00	0.00	0.00	0.00	0.00	0.00	0.00
BAM t_0	0.00	3.00	−0.12	−0.00	−0.00	−0.00	0.00
BPM x BC1	0.64	−8.45	−1.84	−3.16	−5.01	−0.75	0.54
SRC σ_x BC1	−0.09	0.20	−0.02	−0.19	−0.01	0.29	0.01
CDR LW BC1	−0.10	0.21	−0.04	−0.26	−0.04	0.35	0.01
CDR MW BC1	−0.16	0.36	−0.08	−0.52	−0.09	0.67	0.03
CDR SW BC1	0.01	0.08	−0.03	−0.20	−0.04	0.21	0.01
BAM Δt BC1	0.14	−1.86	−0.41	−0.70	−1.11	−0.16	0.12
EO FW ABC1	−0.08	−0.22	0.04	0.25	0.05	−0.26	−0.03

DISCUSSION OF THE RESPONSE MATRIX

Inspection of the response Matrix in Table 3 results in an intuitive approach to control accelerator parameters with a longitudinal feedback:

1. Control the charge generated at the cathode with the BPM charge measurement.
2. Control the arrival time of the laser with the BAM.
3. Control the beam energy with the BPM in the bunch compressor. One important contribution to beam energy is the S-band amplitude, but also S-band phase and bunch arrival time are important factors.
4. When looking at the compression process, the contributions from S- and X-band structures become even more entangled. Use the CDR and EO monitors for feedback.

One helpful approach to analyze this problem mathematically is to perform a singular value decomposition (SVD) [12], i.e. to factor the response matrix R into singular vectors and singular values such that

$$R = U \cdot \Sigma \cdot V^T$$

The matrix Σ is a diagonal matrix that contains the singular values of R. By convention, we sort them by magnitude to arrange the singular vectors according to their importance. The matrix U contains the left singular vectors of R as columns. These describe the linear combination of the diagnostics that can be used for feedbacks. The matrix V consists of rows that are the right singular vectors of R, describing the actuators for these feedbacks.

For the section from the start of the laser heater to the end of the BC1 diagnostics section, this decomposition is shown in Table 4. This reproduces qualitatively the intuitive feedbacks outlined above:

- Singular vector 1 (i.e. row 1 in U and column 1 in V) describes a feedback on the beam energy.
- The charge Q is controlled with the monitor BPM Q (singular vector 2).

ISBN 978-3-95450-117-5

Table 4: Singular Value Decomposition of the Diagnostics Response Matrix: $R = U \cdot \Sigma \cdot V^T$.

U

	1	2	3	4	5	6	7
BPM Q	−0.03	−1.00	0.02	−0.04	−0.03	0	0
BAM t_0	0.22	−0.04	−0.88	0.42	−0.02	−0.03	0
BPM x BC1	−0.95	0.02	−0.20	0.08	0	0	0.04
SRC σ_x BC1	0.01	0.02	−0.13	−0.28	−0.39	0.21	0.08
CDR LW BC1	0	0.02	−0.17	−0.35	−0.35	0.17	−0.78
CDR MW BC1	0.01	0.03	−0.32	−0.69	−0.11	−0.22	0.49
CDR SW BC1	0	0	−0.11	−0.24	0.51	−0.66	−0.35
BAM Δ t BC1	−0.21	0	−0.05	0.01	0	0	−0.16
EO FW ABC1	0	0.02	0.17	0.27	−0.68	−0.66	0.01

Σ

	1	2	3	4	5	6	7
1	11.07	0	0	0	0	0	0
2	0	5.00	0	0	0	0	0
3	0	0	1.91	0	0	0	0
4	0	0	0	0.99	0	0	0
5	0	0	0	0	0.04	0	0
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0

V^T

	Q	t_0	E_0	Φ_S	A_S	Φ_X	A_X
1	−0.07	0.82	0.16	0.28	0.45	0.07	−0.05
2	−1.00	−0.06	0	−0.02	−0.03	0	0
3	0	−0.55	0.28	0.51	0.59	−0.11	−0.07
4	0	0.14	−0.11	0.37	−0.31	−0.86	0
5	0	0	0.16	−0.69	0.46	−0.48	0.21
6	0	0	−0.22	0.21	0.05	0.10	0.95
7	0	−0.04	−0.90	0	0.37	−0.03	−0.22

- The arrival time is controlled with the BAM (singular vector 3).
- Singular vector 4 describes a compression feedback, using the CDR and EO monitors.

For the other three singular vectors, the singular values are so small that they do not contribute.

CONCLUSION AND OUTLOOK

The diagnostics response matrix up to the end of the second bunch compressor has also been calculated. According to the singular value decomposition of this 15×9 response matrix, the measurements of the fully compressed bunch after BC2 have to be used to control the S- and X-band parameters in the injector. As a consequence, a global feedback system needs to be implemented for SwissFEL.

ACKNOWLEDGEMENTS

The authors would like to thank Rafael Abela, Masamitsu Aiba and Luc Patthey for fruitful discussions.

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ISBN 978-3-95450-117-5