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RF JITTER AND ELECTRON BEAM STABILITY IN THE SwissFEL LINAC

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Abstract

The X-ray FEL machine SwissFEL at the Paul Scherrer Institut in Switzerland is commissioned and transiting to user operation smoothly. FEL operation requires stringent requirements for the beam stability at the linac output, such as the electron bunch arrival time, peak current and energy. Among other things, a highly stable RF system is required to guarantee the beam stability. The SwissFEL RF system is designed based on the state-of-the-art technologies that have allowed achieving excellent RF stability. The propagation of RF amplitude and phase jitter to the electron beam are analyzed theoretically and compared with the measurements performed at SwissFEL.

INTRODUCTION

The layout of SwissFEL is depicted in Figure 1 [1,2]. The accelerator consists of an S-band (2998.8 MHz) RF Gun, two S-band Booster sections, an X-band (11995.2 MHz) RF station and 3 C-band (5712 MHz) Linacs. SwissFEL requires highly stable electron beams for FEL generation. The stability goals reported in [3] require at the exit of Linac 3 the beam energy jitter to be < 0.05% rms, the peak current fluctuation < 5% rms and the bunch arrival time jitter < 20 fs rms. In order to meet the stability goals, the RF system must satisfy tight requirements on amplitude and phase stability down to 0.018% RMS in amplitude jitter and 0.018°, 0.036° and 0.072° RMS in phase jitter for S-band, C-band and X-band stations respectively [4].

SwissFEL works in pulsed mode with a repetition rate up to 100 Hz. The pulse-to-pulse jitter of the SwissFEL RF system is dominated by the stability of the klystron driver amplifiers and the high-voltage klystron modulators. The RF pulse width (from 100 ns to 3 μs) is too short to implement efficient and reliable intra-pulse feedbacks. Pulse-to-pulse feedbacks were implemented in the low-level radio frequency (LLRF) system [5] to compensate for the RF fluctuations at frequencies below 1 Hz. For longer time intervals, the drifts of the LLRF detection chain must be corrected by the beam based feedbacks.

In this paper, the measured RF and beam stability for the operation mode with 200 pC will be presented. In order to crosscheck the measurements, a beam dynamics model will be used to predict the beam jitter from the measured RF jitter and compare with the direct beam measurements.

RF STABILITY

The pulse-to-pulse phase and amplitude jitter of the RF field used for beam acceleration is measured with the RF detectors. For each pulse, the RF waveforms are averaged within a time window determined by the time constant of the standing wave cavities (e.g. RF Gun) or within the filling time of the traveling wave structures (1000 ns for S-band, 322 ns for C-band, and 105 ns for X-band). This limits the measurements to the RF-beam interaction bandwidth of the cavities or structures: RF Gun 330.8 kHz, S-band structure 475.8 kHz, C-band structure 1346.5 kHz and X-band structure 4219.0 kHz. Because the drifts slower than 1 Hz are suppressed by the RF feedbacks, the jitter given in this section contains the noise power from 1 Hz to the RF-beam interaction bandwidth of the cavities or structures.

The lab tests of the RF detectors promise a phase resolution of 0.0036° rms and an amplitude resolution of 2.6e-5 rms within the noise band. Compared to the overall RF field jitter, the RF detector added jitter can be neglected.

The pulse-to-pulse RF phase and amplitude jitter measured during this campaign at different RF stations is shown in Figure 2. The red lines show the jitter specification mentioned in the last section.

During the test, the beam based feedbacks were switched off, the phase and amplitude feedbacks of the Gun, S-band and X-band stations were on, while for C-band stations, only the phase feedbacks were on but the amplitude feedbacks were off because the C-band klystrons worked in saturation. Some RF stations did not satisfy the stability requirements and the reasons are summarized below:

- The average window of the RF Gun probe signals was much smaller than the cavity time constant, therefore, the measurement contains high frequency noises including the π/2-mode signal. Furthermore, the RF Gun modulator was not in good condition during the test resulting in higher amplitude and phase jitter.
- The X-band amplitude jitter was slightly above the specified threshold due mainly to the contribution of

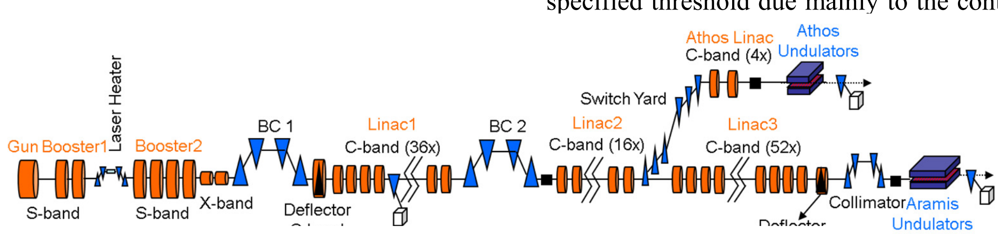

Figure 1: Layout of SwissFEL

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the solid-state amplifier and modulator. As the bunch compression jitter is very sensitive to the X-band jitter, an upgrade path is under investigation.

- The C-band stations worked in saturation, which reduced the amplitude jitter, but the RF station "L1 CB06" had larger amplitude fluctuations due to the defected solid-state amplifier.
- Several C-band stations had multipacting in the Barrel Open Cavity (BOC) placed after the klystron to compress the RF pulse to increase the peak RF power. The multipacting happens when the klystron output power is in the range between about 20 MW and 40 MW, and mainly generates wide-band phase jitter that is not controllable by feedbacks. The klystron output power measurement in Figure 3 shows that the powers of the jittering C-band stations are all below 40 MW.

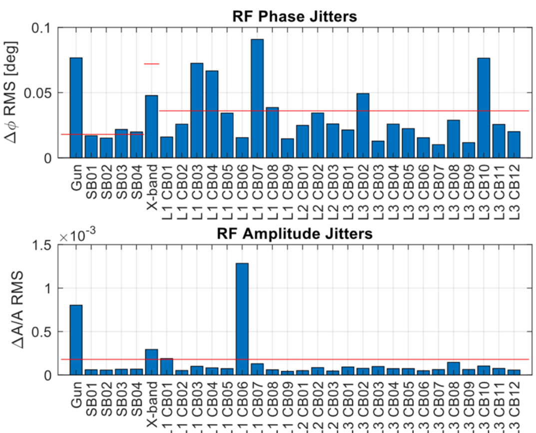

Figure 2: Pulse-to-pulse phase and amplitude jitter of the SwissFEL RF stations.

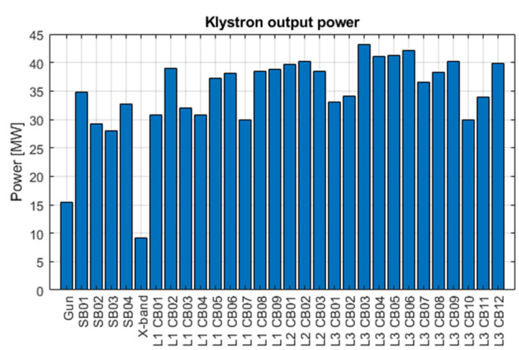

Figure 3: Klystron output powers. The BOCs in C-band RF stations encounter multipacting for powers below 40 MW.

One practical method to mitigate the BOC multipacting is to increase the klystron output power above 40 MW.

As the RF pulse-to-pulse feedbacks can only suppress slow drifts, the fast jitter is dominated by the RF components like the RF actuator (DAC and vector modulator), solid-state amplifier and the klystron modulator. Beside the RF stations with higher jitter mentioned above, the general RF jitter is well within the specifications thanks to the low-noise RF components developed for SwissFEL. The added phase jitter by the RF actuator (S-band and C-band: < 0.006° rms; X-band: < 0.026° rms) and solid-state amplifier (S-band and C-band: < 0.009° rms; X-band: < 0.03° rms) is small compared to the overall RF stability specification. The high voltage jitter of the klystron modulator is therefore the main source of RF jitter, although the absolute jitter is small due to a voltage jitter below 15 ppm at 100 Hz operation [6].

BEAM STABILITY

The jitter of the beam parameters, including the beam energy, peak current and bunch arrival time are measured at the exit of the two bunch compressors (BC1 and BC2). To verify the correlation between the RF and beam jitter measurements, the beam jitter is also predicted with the measured RF jitter and the beam dynamics model.

Beam Dynamics Model

The sensitivity of the beam parameters at different locations with respect to the RF field errors can be described as a matrix by means of longitudinal beam dynamic simulations. With the sensitivity matrix, the deviations of the beam parameters for each pulse can be predicted from the RF field errors measured at the RF stations. Table 1 shows an example of the sensitivity between the BC2 bunch length (peak current) relative deviation and the upstream RF errors and the initial beam parameter errors at the input to the Booster 2. To simplify the study, here we also view the errors in bunch charge, arrival time (converted to equivalent S-band phase) and beam energy at the input of Booster 2 (after the laser heater (LH) in Figure 1) as inputs to the sensitivity matrix.

Table 1: Sensitivity of the BC2 Relative Bunch Length Deviation $(\Delta L/L)_{BC2}$ w.r.t. the Error Sources

Error Source	Notation	Sensitivity
LH Bunch Charge (rel.)	$(\Delta Q/Q)_{LH}$	5.733
LH Bunch Phase (deg)	$(\Delta\varphi_b)_{LH}$	68.079
LH Bunch Energy (rel.)	$(\Delta E/E)_{LH}$	-36.768
Booster 2 Amplitude (rel.)	$(\Delta A/A)_{bst2}$	-100.583
Booster 2 Phase (deg)	$\Delta\varphi_{bst2}$	94.446
X-band Amplitude (rel.)	$(\Delta A/A)_{xb}$	3.774
X-band Phase (deg)	$\Delta\varphi_{xb}$	-56.055
Linac 1 Amplitude (rel.)	$(\Delta A/A)_{L1}$	20.083
Linac 1 Phase (deg)	$\Delta\varphi_{L1}$	32.506

The amplitude and phase jitter in Booster 2 and Linac 1 is the averaged jitter of all RF stations in the corresponding accelerator sections. The sensitivity matrix also provides the information about the more critical RF stations to achieve stable beam qualities. In the example as Table 1, the bunch charge, bunch arrival time at LH and the RF phases of the X-band and S-band Booster 2 are the major contributors to the bunch length jitter after BC2.

Beam Stability

The beam energy, bunch length and the bunch arrival time at the exit of BC1 and BC2 were measured with the

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beam diagnostics and compared with the predicted jitter from the beam dynamics model (see Figure 4).

The beam energy was measured with the BPMs placed in the dispersion region of BC1 and BC2; the relative bunch length was measured with the bunch compression monitor (BCM) [7] at BC1 and the coherent diffraction radiation (CDR) detector at BC2. At SwissFEL, there is a bunch arrival time monitor (BAM) installed before the BC2, which monitors the bunch arrival time jitter at the exit of BC1 with a resolution about 4 fs.

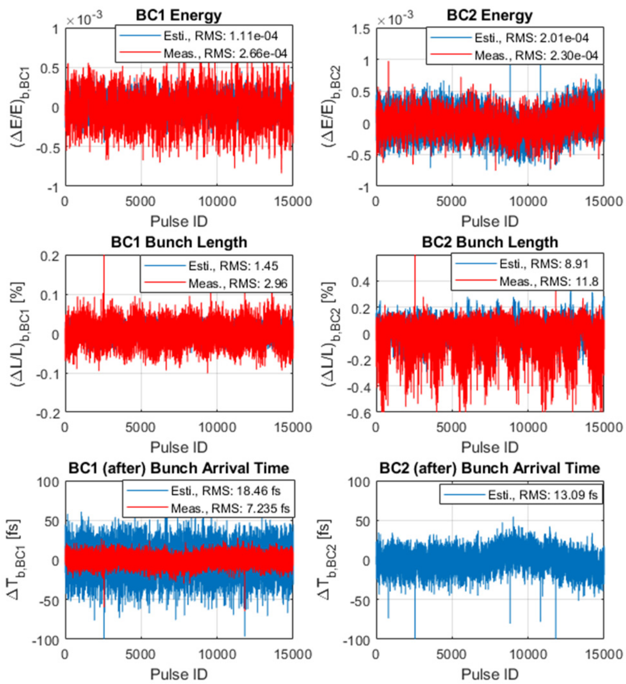

Figure 4: Beam stability measurement (red curve) and prediction (blue curve) at BC1 and BC2. The bunch repetition rate is 25 Hz, bunch charge 200 pC and 10-minute data were collected.

In Figure 4, the measured beam energy jitter and bunch length jitter after BC2 are around 2.3e-4 and 11.8 % respectively. The predicted jitter is slightly smaller than the direct beam measurements, which may be caused by other jitter sources in the machine that are not captured by the sensitivity matrix, or the added noise by the beam diagnostics devices.

The bunch arrival time jitter measurement after BC1 is much smaller than the predicted one. These two results have a good correlation but with different magnitudes. It is planned to measure the sensitivity matrix instead using the theoretical one and make the prediction again. At the exit of Linac 3, the bunch arrival time jitter was measured once with the C-band RF deflectors [8] and the results are shown in Figure 5. The C-band RF deflector is used to measure the absolute bunch length but can also provide the bunch arrival time information. At the exit of Linac 3 and BC2, the bunch arrival time jitter is the same according to the beam dynamics model. Figure 5 indicates a bunch arrival time jitter of 16 fs rms at the exit of BC2. One should be aware that this jitter is a relative value between the actual bunch arrival time and the RF phase jitter in the RF deflector structures. As the RF phase jitter of the C-band RF deflector was measured to be around 0.02° rms, which corresponds to a time jitter of 10 fs rms for the RF frequency of 5712 MHz, the actual bunch arrival time jitter can be estimated to be 13 fs rms. Here we have assumed the actual bunch arrival time jitter and the RF deflector phase jitter are uncorrelated. This estimation matches pretty well to the predicted bunch arrival time jitter after BC2 from the RF jitter and the sensitivity matrix.

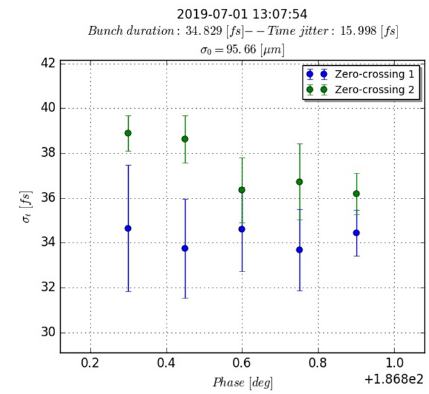

Figure 5: Bunch arrival time measurement with the C-band RF deflector at the exit of Linac 3.

RF-BEAM JITTER CORRELATION

The sensitivity matrix offers the basic information about how significant the RF field jitter contributes to the specific beam parameter jitter. In practice, the measurements of the RF amplitude and phase and the beam parameters can be correlated for each RF pulse. The strength of the correlation shows not only the sensitivity relationship, but also the potential RF stations that have large jitter and require improvements. According to the data in Figure 4, the X-band amplitude and phase jitter shows strongest correlations with the BC2 CDR signal (bunch length) that are shown in Figure 6. Some C-band stations (L1 CB03 and 07) in Linac 1 also have strong correlations (not shown). This information implies the potential improvements that are required for these RF stations.

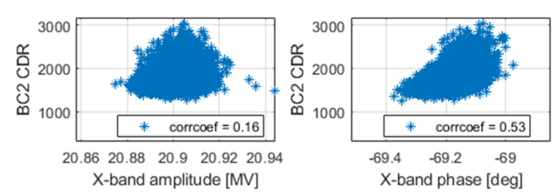

Figure 6: Correlation between the BC2 bunch length jitter and the X-band RF jitter. The X-band jitter has a major contribution to the bunch length jitter.

CONCLUSION

SwissFEL has achieved unprecedented RF and beam stability. The beam energy and bunch arrival time stability meets the requirements, while the bunch length jitter is still over the tolerance. With the systematic RF and beam jitter

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study performed in this work, the critical RF stations for the future improvements are identified.

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