DESIGN OF THE SWISSFEL BPM SYSTEM

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Abstract

SwissFEL [1] is a Free Electron Laser (FEL) facility being constructed at PSI, based on a 5.8GeV normally conducting main linac. A photocathode gun will generate two bunches with 28ns spacing at 100Hz repetition rate, with a nominal charge range of 10-200pC. A fast beam distribution kicker will allow to distribute one bunch to a soft X-ray undulator line and the other bunch to a 0.1nm hard X-ray undulator line. The SwissFEL electron beam position monitor (BPM) system will employ three different types of dual-resonator cavity BPMs, since the accelerator has three different beam pipe apertures. In the injector and main linac (38mm and 16mm aperture), 3.3GHz cavity BPMs will be used, where a low Q_L of ~40 was chosen to minimize crosstalk of the two bunches [2]. In the undulators that just have single bunches and 8mm BPM aperture, a higher Q_L will be chosen. This paper reports on the development status of the SwissFEL BPM system. Synergies as well as differences to the E-XFEL BPM system [3] will also be highlighted.

INTRODUCTION

Table 1 gives an overview of the SwissFEL BPM requirements and specifications. For the BPMs in the undulator intersections ("BPM8"), the performance requirements are driven by beam based alignment and trajectory stabilization, aiming for optimal electron-photon beam overlap and high X-ray pointing stability (<0.1σ) as well as low orbit-induced X-ray intensity fluctuations.

Table 1: BPM Requirements/Specifications

Parameter	BPM38	BPM16	BPM8
Quantity	6	114	50
Length	250 mm	100 mm	100 mm
Inner Aperture	38 mm	16 mm	8 mm
Position Range	±10 mm	±5 mm	±1 mm
Position Noise	<10 µm*	<5 µm*	<1 µm**
Drift/Week	<10 µm	<5 µm	<1 µm
Charge Noise***	<0.1%	<0.1%	<0.1%
Charge Range	10-200 pC		
# Bunches/Train	1-3		1
Train Rep Rate	100Hz		
Bunch Spacing	28 ns		-

* Within 30% of max. position range.
** Within 50% of max. position range.
*** Or 30fC, whatever is larger.

For BPMs in the other parts of the accelerator ("BPM38" and "BPM16"), the specified position resolution will allow to measure the beam energy in the bunch compressors with a relative energy resolution of $<10^{-4}$, by placing BPMs at dispersive locations between the 1st and 2nd as well as the 3rd and 4th bunch compressor dipole. The BPMs will also be used to measure the bunch charge, using other dedicated charge monitors (e.g. current transformers) for absolute calibration. Finally, the BPMs will also be used to correct position or charge dependent readings of other monitors, e.g. beam arrival time monitors or wire scanners. Since SwissFEL will have dedicated beam arrival time monitors based on electro-optical modulators, the BPMs do not need to measure the arrival time, thus simplifying the design and reducing the costs of the BPM system and its reference clock distribution.

BPM PICKUPS

The design of the SwissFEL cavity BPM pickups [2] is based on designs from SACLA/SPring-8 [4] and E-XFEL [5], but was optimized e.g. for improved resolution at low bunch charge and low production costs. The pickups have two resonators: The TM_{010} (monopole) mode of the "reference resonator" is used to measure the bunch charge, while the horizontal and vertical TM_{110} (dipole) modes of the "position resonator" provide the product of bunch charge Q and position in the horizontal (X) or vertical (Y) plane. In the position cavity, the dipole modes for X and Y plane are coupled out using four waveguides that are machined into the pickup body at 90° angles, with one RF feed-through per waveguide. The waveguide coupling suppresses the monopole mode that would otherwise limit the performance of the BPM system.

For the present prototypes, we successfully used very cost-efficient RF feed-throughs designed at PSI and fabricated by a Swiss company, with glass ceramics as isolator between inner and outer conductor. The three parts of the stainless steel pickup body are brazed together using foils. The feed-throughs are then welded to the pickup body. Due to comparatively relaxed mechanical tolerances, the pickups do not need any frequency tuning during or after production, with typical deviations of a few MHz from the nominal frequency and <10% from the nominal loaded quality factor Q_L.

Figure 1 shows longitudinal cuts through the BPM38 and BPM16 pickups. BPM8 is similar to BPM16 but has somewhat different dimensions, as shown in the overview of pickup parameters in Table 2, Table 3 and Table 4. BPM38 is longer than BPM8 and BPM16 (255mm vs. 100mm) since the larger aperture needs a larger spacing of the two resonators in order to reduce the crosstalk from reference to position cavity to a negligible level that corresponds to ~100nm beam offset error.

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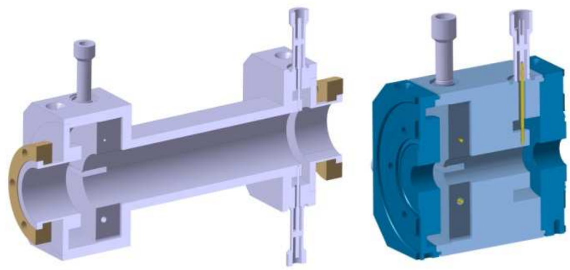

Figure 1: Longitudinal cross section of BPM38 (left) and BPM16 (right) cavity pickup.

The RF parameters in the tables were obtained from HFFS simulations. “Gap” denotes the distance between the resonator walls that is crossed by the beam. The chosen gap size is a compromise between high position sensitivity and high ratio of position to (undesired) angle signal generated by a beam with no offset but at an angle to the pickup axis. The angle signal has 90° phase to the position signal (induced by the offset of a beam without angle). Since it has a negative impact on the performance, it will be minimized by beam-based pickup angle alignment and digital suppression methods.

Table 2: General Pickup Parameters

Parameter	BPM38	BPM16	BPM8
Material	Stainless Steel 316LN		
Distance From Position To Ref. Resonator [mm]	180	60	50

Table 3: Position Cavity Resonator Parameters

Parameter	BPM38	BPM16	BPM8
Gap [mm]	14	7	14
Q_L	40		200
TM_{110} Frequency [GHz]	3.284		
TM_{010} Frequency [GHz]	2.389	2.252	2.202
Position Signal [V/mm/nC]	5.74	7.07	5.23
Angle Signal [μm/mrad]	15.5	4.3	9.5

Table 4: Reference Cavity Resonator Parameters

Parameter	BPM38	BPM16	BPM8
Gap [mm]	7		
Q_L	40		200
TM_{010} Frequency [GHz]	3.284		
Charge Signal [V/nC]	66.4	135	47.5
No. of Couplers	2	1	1

Using the same frequency of 3.284GHz for the operation mode of reference and position resonator minimizes drift of the measured beam position, since frequency-dependent gain drifts of the symmetrically designed position and reference signal channels in the BPM electronics cancel out when the beam position is calculated from the ratio of the signals.

Pickup Type Considerations

For the BPMs in the undulator intersections, dual-resonator cavity BPMs are a common choice due to their potential to reach sub-micron resolution and drift over a wide charge range with reasonably low design effort and investments. For injector and linac, the more relaxed performance requirements would also have allowed the use of stripline BPMs that are used e.g. in the SwissFEL Injector Test Facility (SITF) [6]. However, the development of the final SwissFEL systems had just started when SITF became operational. Therefore SITF was equipped with a BPM system largely based on existing (older) hardware that was not intended and is not suitable for SwissFEL due to electronics age, limitation to 10Hz single-bunch operation, integrated profile monitor that will be different for SwissFEL, etc. Due to comparable costs of stripline and cavity BPM pickups, we decided to use only cavity BPMs in SwissFEL, thus obtaining a homogeneous high-performance BPM system. Moreover, the similar beam pipe apertures of E-XFEL and SwissFEL allowed to choose the same 3.3GHz working frequency for E-XFEL and SwissFEL pickups. Therefore SwissFEL can re-use E-XFEL cavity BPM electronics presently developed by PSI with small modifications, thus maximizing synergies and minimizing development and long-term maintenance efforts.

Two Bunch Operation and Crosstalk

One specific challenge for the SwissFEL BPM system is the independent position and charge measurement of two bunches with 28ns bunch spacing for BPM16 and BPM38. For bunches with roughly equal charge, the desired bunch-to-bunch crosstalk (after application of crosstalk suppression techniques in the BPM electronics) should ideally be smaller than the resolution, so that position, charge and energy of both bunches can be measured independently. Therefore the Q_L of BPM38 and BPM16 was reduced to 40, compared to 70 for E-XFEL, to minimize bunch-to-bunch crosstalk. When the 2nd bunch arrives after 28ns, the signal of the 1st bunch has already decayed to 0.07% (-63dB) of its initial amplitude for Q_L=40, compared to 1.6% for Q_L = 70.

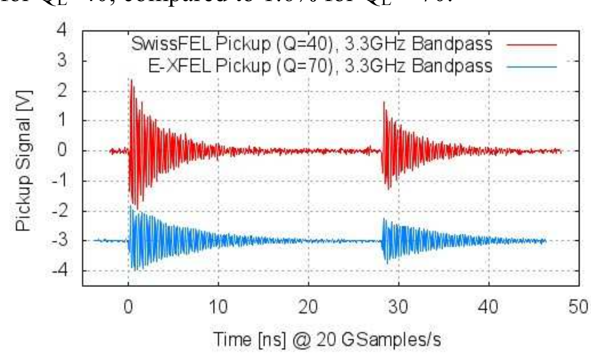

Figure 2: Signals of SwissFEL BPM16 pickup (top) and E-XFEL undulator pickup (bottom).

Figure 2 shows the oscilloscope signals of a SwissFEL BPM16 and an E-XFEL undulator BPM pickup,

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measured at a BPM test area at SITF (see Figure 3). The measured position and charge sensitivity as well as Q_L are consistent with HFSS simulations and lab tests.

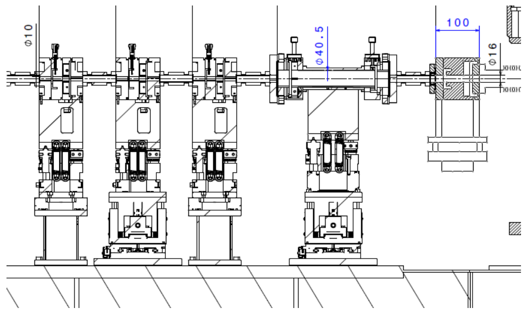

Figure 3: BPM test area at SITF. Left to right (beam direction): Three E-XFEL undulator cavity BPMs, one E-XFEL beam transfer line BPM (255mm long), one SwissFEL BPM16 pickup (support not shown).

Development Status

The BPM16 pickup for which the largest quantities are needed has so far been fabricated in smaller pre-series quantities and will soon go into series production. For BPM38, the mechanical construction is in progress. For BPM8, a prototype with Q_L=70 has been fabricated and tested in the lab [2], while the final version with Q_L=200 will soon be fabricated.

Undulator Pickup Q_L

The baseline version of the BPM8 pickup consists of stainless steel to simplify design and production by keeping it similar to BPM16 and BPM38. Since BPM8 sees only one bunch, its Q_L may be higher than for BPM16 and BPM38. A higher Q_L is attractive since it increases the ratio of position range to resolution at high charge, because more ADC samples can be used to calculate the position, thus reducing the impact of the ADC noise on the position noise. On the other hand, the low charge resolution for steel cavities gets worse for higher Q_L due to increasing resistive cavity wall signal losses. Therefore we decided to use Q_L =200, where the resolution at very low charge is only 15% worse than for a copper cavity.

While the stainless steel version of BPM8 represents the baseline design for SwissFEL, we also started R&D on an alternative pickup using copper (or copper-coated steel) with even higher Q_L and higher frequency (e.g. ~4.8GHz). While the different material would cause more work for development and production, the higher frequency would improve the resolution at low charge, and the higher Q_L would increase the ratio of position range to noise at high charge.

BPM ELECTRONICS

The SwissFEL BPM electronics will be based on the E-XFEL cavity BPM electronics that is presently being developed by PSI [3][7][8], with some SwissFEL-specific adaptations of the hardware and firmware e.g. for the shorter bunch spacing (for BPM16 and BPM38), lower bunch charge, higher Q_L (for BPM8) and different interfaces to the control, timing and feedback systems. Figure 4 shows a simplified block schematics of the cavity BPM RFFE that we used for beam tests of a BPM16 pickup prototype. Figure 5 shows the BPM electronics for two cavity BPMs. The standalone unit provides SFP(+) interfaces, supporting Ethernet, PCIe, or custom protocols for control, timing and feedback system interfaces.

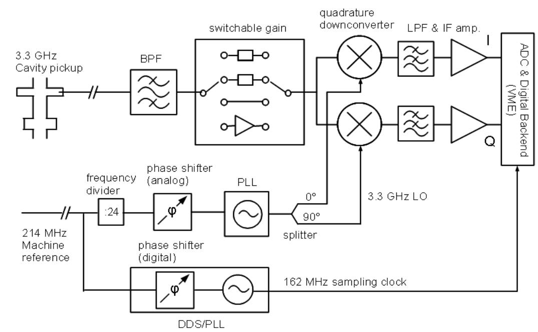

Figure 4: Simplified schematics of cavity BPM RFFE.

The RFFE filters the pickup signal, adjusts the signal level via amplifiers and variable attenuators, and performs IQ downconversion to baseband (for BPM16 and BPM38), using a locally generated LO frequency locked to an external machine reference clock. After mixing, the signals go through another lowpass/bandpass filter. The resulting RFFE output signals are connected via differential signalling to a digitizer board with 16-bit 160MSample/s ADCs and FPGAs for digital signal processing and interfacing to control, timing and feedback systems. For BPM8 with its higher Q_L, we are considering mixing to an IF and using digital downconversion as alternative to the signal processing of BPM16 and BPM38.

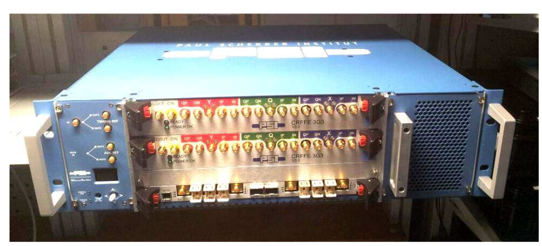

Figure 5: PSI Cavity BPM electronics for two cavity BPMs, with digitizer/FPGA board (bottom) [8] and two RFFEs (top) [7], and disconnected cables from RFFE to ADCs.

For BPM16 and BPM38, an FPGA on the digital ADC carrier board continuously and automatically adjusts the LO phase as well as the bunch-synchronous ADC sample clock phase, in order to sample the RFFE output signals pulses exactly at the top and with fixed IQ phase for minimal systematic errors due to IQ imbalance (that will nevertheless be corrected by the FPGA using calibration lookup tables). While the SwissFEL RFFE prototype we used so far had four gain ranges with 23dB overall range and ~8dB steps, the final version that was recently tested (so far with E-XFEL pickups) has 63dB range with 0.5dB

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steps for each RFFE channel. This allows to use the full ADC range over wide position and charge ranges.

FIRST BEAM TEST RESULTS

2-Bunch Operation and Crosstalk

The present SwissFEL BPM16 RFFE prototype (also to be used for BPM38) uses the same PCB as the E-XFEL cavity BPM RFFE, but the passband frequency range of the filter downstream of the IQ mixer was changed from 10-45MHz to 0.3-80MHz by soldering different components, thus reducing bunch-to-bunch signal crosstalk that is dominated by the filter. Figure 6 shows the RFFE output signal of the reference pickup signal for the SwissFEL RFFE and BPM16 pickup.

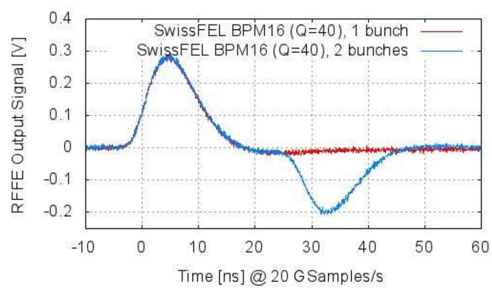

Figure 6: RFFE output signal of SwissFEL BPM16 (only Q signal of RFFE IQ signal outputs shown).

The signals were recorded at SITF, with 28pC in the 1st bunch, 22pC in the 2nd bunch, and 28ns bunch spacing. The SwissFEL BPM has about 10 times less overlap of the signals of the two bunches than the E-XFEL BPM, thus enabling an easier and better separation and crosstalk suppression of the signals of the two bunches. Since the only non-negligible signal crosstalk for the SwissFEL BPM is caused downstream of the RFFE mixer, the crosstalk can simply be removed by subtracting a certain percentage p(n) of the peak amplitude of the 1st bunch from the ADC samples at the location of the signal pulse of the 2nd bunch. p(n) depends on the sample number n, but is rather insensitive to the bunch spacing since the crosstalk is purely additive (exponential decay) for each ADC channel, without constructive/destructive interference like for high-Q cavities. It should be noted that for SwissFEL the signal pulses of the two bunches will have the same polarity and IQ phase. This is achieved by choosing 3.284GHz for the (programmable) LO phase frequency and pickup frequency, since this is an integer multiple of the SwissFEL machine reference clock of 142.8MHz. For our STIF tests, we used 3.3GHz LO frequency with a 214MHz reference, resulting in different IQ phases for the signals of the two bunches as shown in Figure 6.

Position and Charge Resolution

Charge and position resolution measurements of a complete SwissFEL BPM16 system with the modified RFFE were conducted at SITF. The BPM16 charge noise was determined by correlation with E-XFEL BPMs and is <0.07% at higher charges where the relative resolution is charge independent, and 8fC RMS at very low charge where the absolute charge resolution is charge independent. The product of charge and position resolution of BPM16 is <15µm·pC (compared to 22µm·pC for the E-XFEL undulator BPMs), which is already better than the requirement of 50µm·pC. At 135pC, the position resolution of BPM16 is <0.8µm RMS for 0.35mm beam offset. The resolution was determined by comparing the BPM16 position readings with a predicted position obtained from a linear combination of the readings of adjacent E-XFEL BPMs (see Figure 7).

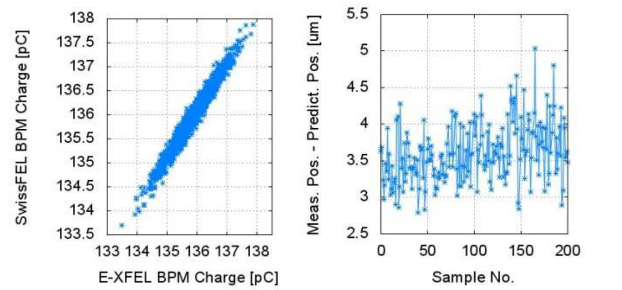

Figure 7: Left: Charge noise correlation of E-XFEL and SwissFEL BPM that has <0.1pC resolution at 136pC. Right: Measured minus predicted position at BPM16.

SUMMARY AND OUTLOOK

First beam tests of a SwissFEL linac BPM16 prototype at the SwissFEL Injector Test Facility showed that the necessary charge and position resolution has already been reached or exceeded, for an electronics that was optimized for low bunch-to-bunch crosstalk. Further beam tests of BPM16 and of future BPM38 and BPM8 (undulator) pickup prototypes that are currently being developed are planned for 2014, where parameters like drift, linearity, arrival time dependence, and 2-bunch position and charge crosstalk will be characterized.

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