DEVELOPMENT OF THE SWISSFEL UNDULATOR BPM SYSTEM

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Abstract

For SwissFEL, two types of cavity BPMs are used. In the linac, injector and transfer lines, low-Q dual-resonator cavity BPMs with a loaded-Q factors (Q_L) of ~40 and 3.3GHz mode frequency allow easy separation of the two adjacent bunches with 28ns bunch spacing. For the undulators that receive only single bunches from a beam distribution kicker with 100Hz repetition rate, dual-resonator BPM pickups with higher Q_L are used. The baseline version for the undulator BPMs is a stainless steel pickup with Q_L=200 and 3.3GHz frequency. In addition, an alternative version with copper resonators, Q_L=1000 and 4.8GHz frequency has been investigated. For all pickups, prototypes were built and tested. The status of pickup and electronics development as well as the latest prototype test results are reported.

INTRODUCTION

Due to different apertures in different parts of SwissFEL, three different BPM pickups are needed. While the injector and linac have BPM pickup apertures of 38mm ("BPM38") and 16mm ("BPM16), the undulator BPMs have 8mm ("BPM8").

Injector and Linac BPMs

The planned cavity BPM system for injector and linac is similar in architecture to that already developed by for E-XFEL and FLASH2 [1,2,3,4]. In order to independently measure position and charge of the two bunches with 28ns spacing (compared to 222ns for E-XFEL), the SwissFEL BPM38 and BPM16 pickups have a lower Q_L of ~40, compared to Q_L=70 for E-XFEL. The signal frequency is f_o=3.284 GHz for BPM38 and BPM16, which is still safely below the cut-off frequency of the larger (38mm aperture) beam pipe. Moreover, this frequency is an integer multiple of the machine reference clock frequency (142.8MHz), where the bunch spacing is four reference clock periods. As a result, both bunches have (nearly) the same IQ phase, which simplifies the algorithms for BPM signal processing and local oscillator phase feedback (see ref [3]). Finally, the choice of this frequency also allows direct reuse of large parts of the E-XFEL cavity BPM electronic system that also work at 3.3GHz (with a similar aperture of 40.5mm for the warm E-XFEL beam transfer lines), thus minimizing the development effort.

For Q_L=40 and f_o=3.284 GHz the resulting decay time $\tau=Q_L/(\pi\cdot f_o)$ of the BPM38 and BPM16 pickup signals is 3.9 ns. After 28ns, the cavity signal is decayed to <0.1% of the initial amplitude before the second bunch arrives, thus causing only negligible RF crosstalk between bunches. In order to be able to use the same 160MSPS ADCs like for E-XFEL, the RFFE shapes the output pulses for the two bunches such that enough samples for a sufficiently accurate computation of the beam position are available, using a simple algorithm in the BPM electronics FPGAs to eliminate any bunch-to-bunch crosstalk caused by the pulse shaper. Compared to pickups with high Q where overlapping pickup signals can have constructive or destructive interference, the low-Q RFFE output pulse shaper only causes small overlap of baseband amplitude signals, where a simple (scalar) subtraction of the overlapping signal pulses is sufficient to supress bunch-to-bunch crosstalk, without the necessity to use phase information.

The RMS noise requirements of the SwissFEL linac BPMs is <5µm for the 16mm aperture cavity and <10µm for the 38mm cavity (see Table 1) at 10-200pC bunch charge. Tests with a slightly modified E-XFEL BPM electronics have already demonstated sub-micron resolution for a BPM16 prototype pickup installed at the SwissFEL Injector Test Facility SITF [1].

Undulator BPMs

The BPMs in the SwissFEL undulator intersections have higher resolution and precision requirement than the linac and injector sections (see Table 1). From the experience gained with the E-XFEL and FLASH2 cavity BPM system we decided to use BPM pickups of the same basic structure, but with higher Q_L. The main reasons for this decision are:

1. In contrast to EXFEL, the SwissFEL undulators are operated in single bunch mode with 100Hz repetition rate, therefore we do not need a low Q_L to avoid bunch-to-bunch crosstalk of pickup output signals.
2. With higher Q_L, more data samples are available per bunch when using a similar ADC sampling rate. This reduces the impact of ADC noise on the BPM position noise and thus increases the ratio of measurement range to noise (for higher bunch charges), which is typically ~1000 for Q_L~40-70.
3. Direct digital quadrature downconversion from a finite IF frequency is able to eliminate systematic measurement errors due to phase and amplitude imbalance. Position and charge readings are thus less sensitive to sampling phase or bunch arrival fluctuations, increasing robustness and overall accuracy.

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Table 1: SwissFEL BPM Pickup Specifications (EXFEL undulator pickup shown for comparison only)

Type	Aperture (mm)	Q_L	Freq. (GHz)	Bunch spacing	Resonator Sensitivity Reference (V/nC)	Resonator Sensitivity Position (mV/nC/ µm)	RMS Position Noise (µm)	Location
BPM8	8	200	3.284	1 bunch 100Hz	47.5	5.2	<1	Undulators
BPM8	8	1000	4.855	1 bunch 100Hz	58	4.3	<1	Undulators
BPM16	16	40	3.284	28ns (2 bunch mode)	135	7.1	<5	Injector/Linac
BPM38	38	40	3.284	28ns (2 bunch mode)	66	5.7	<10	Injector/Linac
EXFEL	10	70	3.3	222ns	45	2.8	<1	Undulators

It should be noted that choosing a higher Q_L (for a given pickup geometry, by having weaker coupling) does not affect the BPM position noise at very low bunch charges, or at higher bunch charges and small measurement ranges where RFFE noise dominates over ADC noise.

UNDULATOR PICK-UP DESIGN AN STATUS

Recently we have successfully tested two BPM8 undulator pickup prototypes at the SwissFEL Injector Test Facility (SITF) with beam: One made from stainless steel, with Q_L~200 and f=3.284GHz, and one with copper resonators and an outer stainless steel hull with Q_L~1000 and f=4.855GHz (see Figure 1).After getting experience with the production and confirming that the copper version can be produced on time and on budget, we decided to use it in the SwissFEL undulators since it allows to reach better resolution than the 3.3GHz steel version both at high charge (due to the higher Q_L) and at low charge (due to the higher frequency that improves sensitivity for a given decay time). A detailed discussion of further design considerations may be found in [1].

The design of the SwissFEL cavity pickup was based on the experience gained during the E-XFEL cavity BPM project over the last few years - as is true for the entire PSI SwissFEL BPM activities. The pickup bodies for BPM38, BPM16 and the BPM8 version with Q_L=200 are all made from stainless steel (316LN). Details of the design are given in [1,5,6,7]. Q_L=200 is a compromise between the goals of having a high Q_L and keeping the resistive losses reasonably low. In order to reach a much higher Q_L of ~1000, we designed a BPM8 pickup with copper resonators.

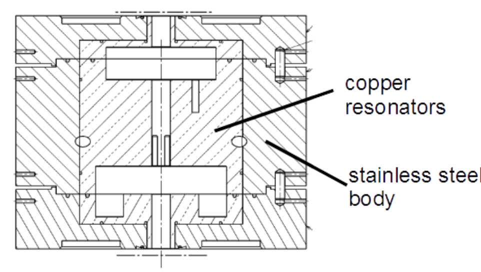

Figure 1: Cross-section of BPM8 Q_L=1000 pickup.

As shown in Figure 1 the pickup has an outer hull and vacuum flanges made from stainless steel, while the inner part with the resonators is made from copper. This combines the advantages of copper resonators – easy machining and low losses – with the advantages of stainless steel for the outer part of the pickup – easy welding of the RF feedthroughs, and solid vacuum flanges.

Table 2: Status of SwissFEL cavity BPM pickups

Cavity	Quantity for at SwissFEL	Status
BPM16	111	Prototype installed at SwissFEL Test Injector Facility (SITF). Test OK, series production started
BPM38	6	Prototype installed at SITF. Test OK. Production started
BPM8 (Q_L=200) or BPM8 (Q_L=1000)	27	Prototype installed at SITF. Preliminary Test OK Prototype installed at SITF. Preliminary test OK.

During production, the copper block is first brazed into the steel hull. After machining the three body parts, they are brazed together. Then the glass ceramic RF feedthroughs are welded to the body, followed by a final vacuum test. The current status of the SwissFEL cavity pickups is summarized in Table 2.

All SwissFEL undulator BPM8 pickups will be horizontally and vertically adjustable using high-precision motorized movers. This allows absolute calibration of the undulator BPM position during operation. The BPM16 and BPM38 pickups will have supports that can only be adjusted manually for cost reasons.

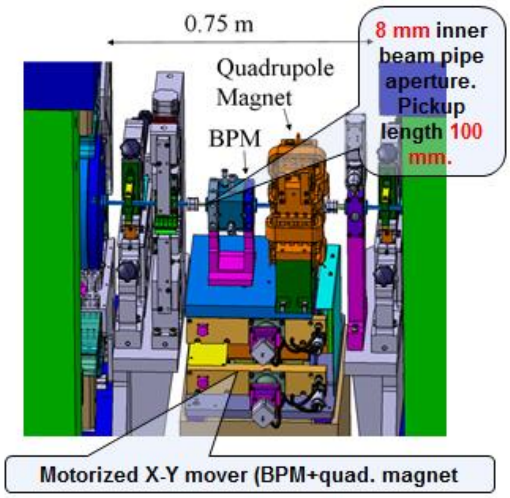

Figure 2: SwissFEL undulator BPM8 pickup in an undulator intersection, mounted together with a quadrupole magnet on a motorized 2D mover stage.

LOW-Q & HIGH-Q RF FRONT-END ELECTRONICS

To process the BPM38 and BPM16 pickups signals, a slightly modified version of the already existing E-XFEL cavity BPM RF electronics will be used [3,4]. A block diagram of this electronics is shown in Figure 3.

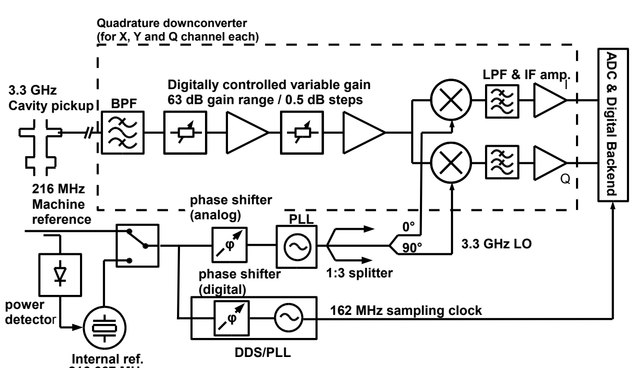

Figure 3: RFFE electronics use for low-Q BPM.

The short RF pulse signal (compared to the ADC sampling interval) produced by a low-Q pickup makes it adequate to use analog I/Q downconversion. If high-Q cavities are used it becomes however more attractive to do the downconversion in the digital domain. A block schematics of the BPM8 electronics (with 3.3GHz and Q_L=200 or 4.8GHz and Q_L=1000) is shown in Figure 4.

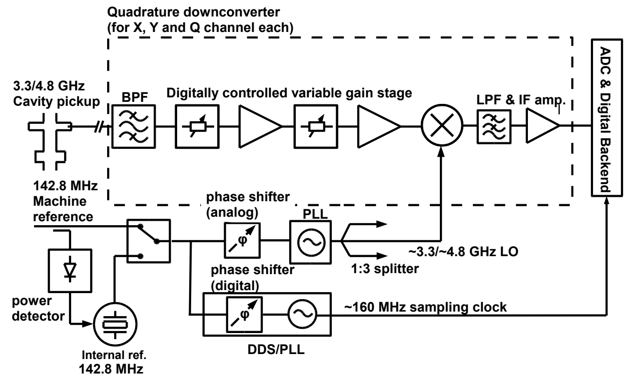

Figure 4: High-Q RFFE electronics.

Instead of using an I/Q downconverter, a single mixer is sufficient to convert the pickup signals to an IF frequency of ~40MHz. The IF portion (downstream of the mixers) uses different filter characteristics, which represents only a slight change in circuit design compared to the low-Q RFFEs.

For the 3.3GHz BPM8 pickup, large parts of the E-XFEL / FLASH2 CBPM electronics could have been reused due to the same signal frequency. For the 4.8GHz version that is now the baseline for SwissFEL, parts in the RFFE input stage (filters, amplifiers, mixers) need to be adapted or exchanged in order to support the higher frequency. The development of the 4.8GHz RFFE is in progress. Presently we are using synthetic high-Q cavity signals from a signal generator at 3.3 GHz together with the present 3.3GHz EXFEL cavity BPM RFFE electronics which can thus generate the same output signals like the future 4.8GHz version. This allows tests of the high-Q firmware and digital signal processing in parallel to the development of a new 4.8GHz RFFE.

LOW-Q BPM SIGNAL PROCESSING

The low-Q BPM systems need to process data under multi-bunch operation. In case of the EXFEL BPM systems there is a need to process the data with minimal processing latency. Presently, only one ADC sample at the very top of the RFFE output signal is used for calculation of vector magnitude and vector angle [3, 4].

However, while this approach provides minimal latency for the E-XFEL intra-bunch train feedback, it is also “wasting” the information contained in other sampling points of nonzero magnitude. Collecting the information of all sampling points by applying matched filter technique can reduce the position noise of the BPMs by approximately 30%. Since the present system performance already meets the E-XFEL requirements, the implementation of such a filter – that will cause a moderate increase of the system latency - is planned for a future firmware version.

The signals from SwissFEL BPM16 and BPM38 (both having a loaded-Q factor of ~40) are captured using the same approach and, in large parts, identical hard- and firmware as is used in the EXFEL/FLASH2 cavity BPM systems. Figure 6 shows double bunch signal from BPM16 under real beam conditions at SITF.

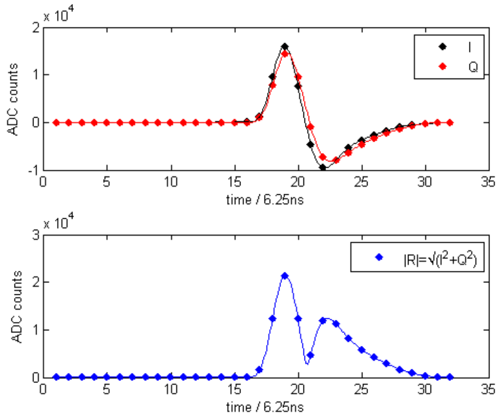

Figure 5: Low-Q signals and sample values (EXFEL electronics [4]).

As can be seen only the sampling points at the top have optimal signal-to-noise ratio. Therefore, a matched filter processing would increase resolution only by about 30%. The process of RF phase and sampling phase alignment (described in [3]) for SwissFEL BPM38 and BPM16 are identical to the EXFEL cavity BPM system.

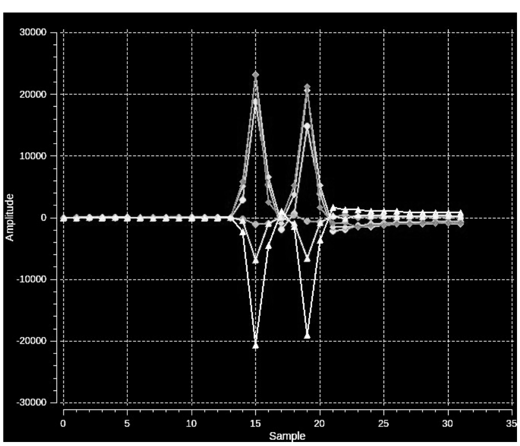

Figure 6: Screen showing the ADC samples of BPM16 (Q_L=40) at SITF in two-bunch mode (28ns bunch spacing).

HIGH-Q BPM DATA PROCESSING

For the planned SwissFEL high-Q undulator cavity BPM system it is intended to apply digital quadrature downconversion from a cavity signal that has previously been mixed by the RFFE to an IF frequency of ~40MHz. Figure 7 shows a principle diagram of the data processing chain. The ADC samples of the IF pulse waveform are stored in an array. The stored values are then parallel multiplied by an array of data containing a sine or cosine waveform, thus representing a numerical controlled oscillator. Afterwards the resulting values are processed by a FIR low-pass filter in order to remove the sum frequency content. This FIR filter may also implement a matched filter at the same time. The filter output is then fed to the interpolation and peak-detection algorithm from where vector magnitude and phase is extracted. The firmware following this stage is intended to be similar in large parts to the already existing implementation of the EXFEL/FLASH2 cavity BPM system. A first version of the high-Q BPM signal processing algorithm has been implemented in software on the generic E-XFEL BPM FPGA board that is also suitable for SwissFEL [1,3]. Laboratory and beam tests at PSI are ongoing.

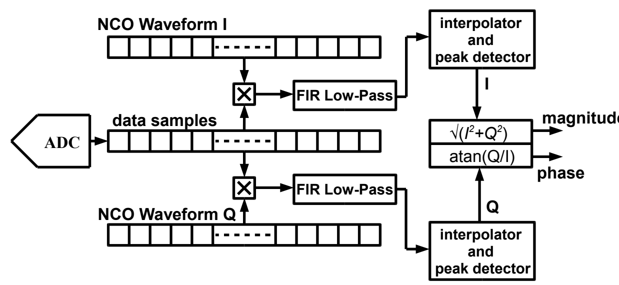

Figure 7: High-Q signal processing scheme.

PICKUP BEAM TESTS

Waveform and signal frequency spectra for SwissFEL and E-XFEL BPM pickups have been measured under real beam conditions at SITF. Figure 8 through Figure 11 shows the signal of the reference and position cavity for the two prototypes of the SwissFEL undulator BPM pickups.

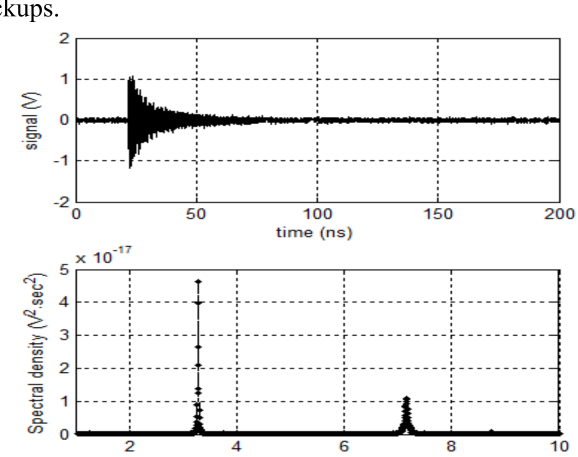

Figure 8: BPM8 (Q_L=200, 3.284GHz) Reference Signal waveform and spectrum (8 GHz oscilloscope).

Figure 12 shows the results from the preliminary implementation of the intended high-Q BPM signal processing (Figure 7) using the EXFEL RF electronics of Figure 3. The top screen contains the raw signal samples from I- and Q output at an intermediate IF frequency of

~40MHz. Only the I-waveform is used for further processing. The NCO waveforms are seen in the screen below. The bottom screen shows the output of the FIR filter stages, representing the in phase and quadrature component from which vector magnitude and vector angle are calculated. The FIR filter in this example has been chosen to implement a low-pass section followed by a matched filter.

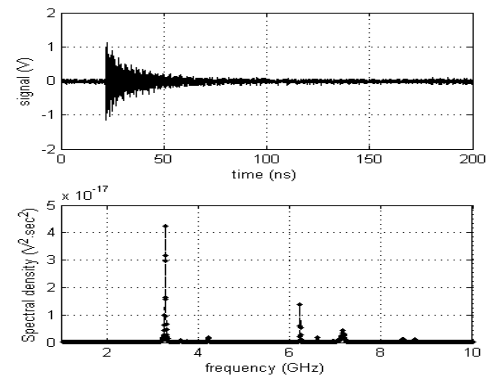

Figure 9: BPM8 (Q_L=200, 3.284GHz) Position Cavity Signal Waveform and Spectrum (8 GHz oscilloscope).

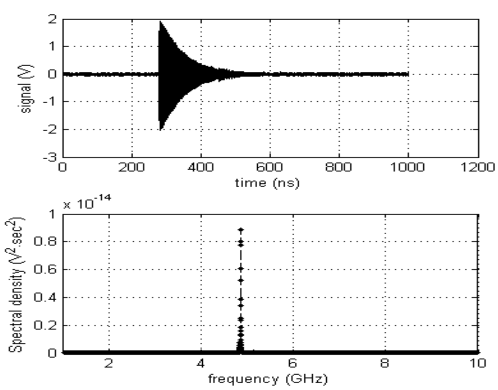

Figure 10: BPM8 (Q_L=1000, 4.855GHz) Position Cavity Signal Waveform and Spectrum (6 GHz oscilloscope).

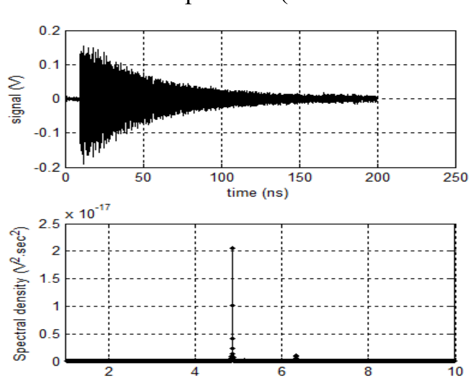

Figure 11: BPM8 (Q_L=1000, 4.855GHz) Position Cavity Signal Waveform and Spectrum (6GHz oscilloscope).

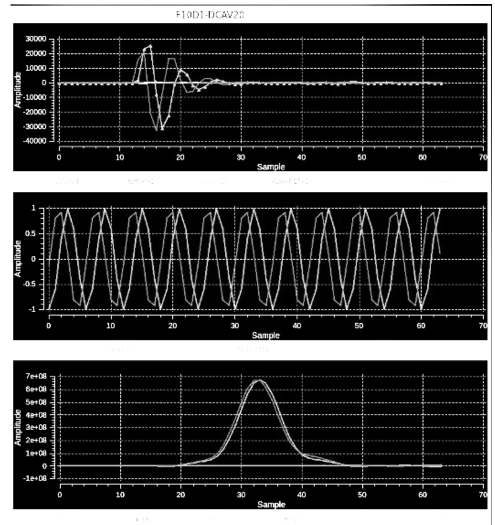

Figure 12: BPM8 (Q_L=200) Test System Waveform Window.

SUMMARY

An overview or the planned SwissFEL undulator BPM system has been given. A comparison to the existing EXFEL/FLASH2 BPM system has been made. The intended high-Q signal processing scheme has been described. Finally beam measurements of two SwissFEL undulator BPM pickup prototypes with Q_L values of 200 and 1000 have been presented.

Test and development activities on this high-Q BPM system are ongoing at PSI using EXFEL cavity BPM electronics and a preliminary signal processing implementation on a E-XFEL BPM FPGA board.

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