LOW-Q CAVITY BPM ELECTRONICS FOR E-XFEL, FLASH-II AND SwissFEL*

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Abstract

PSI has developed BPM electronics for low-Q cavity BPMs that will be used in the E-XFEL and FLASH2 undulators, as well as in SwissFEL injector, linac and transfer lines. After beam tests at the SwissFEL test injector (SFIT) and FLASH1, a pre-series of the electronics has been produced, tested and commissioned at FLASH2 [1]. The design, system features, signal processing techniques, lab-based test and calibration system as well as latest measurement results are reported.

INTRODUCTION

The European XFEL (E-XFEL) has a superconducting 17.5GeV main linac that will provide trains of up to 2700 bunches, with 0.1-1nC bunch charge range, 600µs train length, ≥222ns bunch spacing, and 10Hz train repetition rate. A kicker/septum scheme can distribute fractions of the bunch train to two main SASE undulator lines followed by "secondary undulators" for spontaneous or FEL radiation. The E-XFEL will provide SASE radiation down to below 0.1nm wavelength and supports arbitrary bunch patterns within a bunch train, with bunch spacing of n*111ns, where n is an integer >1.

The cavity BPM electronic system is being developed at PSI [2, 3, 4]. For detailed performance measurements of the E-XFEL undulator BPM system an array of 3 pickups have been installed both at the SwissFEL injector test facility [3] and FLASH1 [1]. 22 E-XFEL undulator BPM systems have recently been installed at the FLASH2 section [1].

CAVITY PICKUP

The 3.3 GHz cavity pickups used for FLASH2 and EXFEL undulator and transfer line sections were designed at DESY [5]. Sensitivity parameters are given in Table 1.

Table 1: EXFEL Cavity BPM Pickup Parameters (10mm Beam Pipe Aperture)

	position cavity (TM110 mode)	reference cavity (TM010 mode)
Resonant frequency	3300 MHz	3300 MHz
Sensitivity	2.8 mV/nC/µm	42 V/nC
Cavity loaded-Q	70	70
Aperture	10mm (undulator) and 40.5mm (transfer line)	

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* This work was partially funded by the Swiss State Secretariat for Education, Research and Innovation SERI

Due to the low bunch rate of only 28ns (double-bunch operation) the cavity pickup used in the SwissFEL linac and transfer line sections have a loaded-Q (Q_L) factor of 40. SwissFEL undulator BPMs use high-Q cavities with a Q_L of ~1000 and a frequency of 4.8 GHz.

Table 2: SwissFEL low-Q cavity pickup data

	BPM38	BPM16
Frequency (GHz)	3.284 GHz	3.284 GHz
Min. bunch separation (ns)	28 ns	28 ns
loaded-Q	40	40
aperture	38 mm	16 mm
Sensitivity (reference resonator in mV/nC/µm)	5.7	7
Sensitivity (position resonators in V/nC)	66	135

BPM ELECTRONICS

The present BPM electronics prototype consists of:

- The RF front-end electronics (RFFE): One I/Q downconverter for reference, x- and y-position signal channel, using a common LO synthesizer, and an ADC sampling clock synthesizer. Active local temperature stabilizer circuits are employed on the RFFE PCBs for drift reduction.
- 6-channel, 16-bit 160MS/s analog-to-digital converters for all RFFE I and Q baseband differential output signals.
- Digital signal processing hardware ("GPAC" board) for signal processing and interfacing to control, feedback, timing and machine protection systems.

Detailed description of the overall electronics is given in [2, 3, 5].

RF Frontend (RFFE)

The simplified block diagram of the RFFE electronics used is shown in Figure 1. The basic principle of the BPM electronics and cavity design is based on [3].

ISBN 978-3-95450-141-0

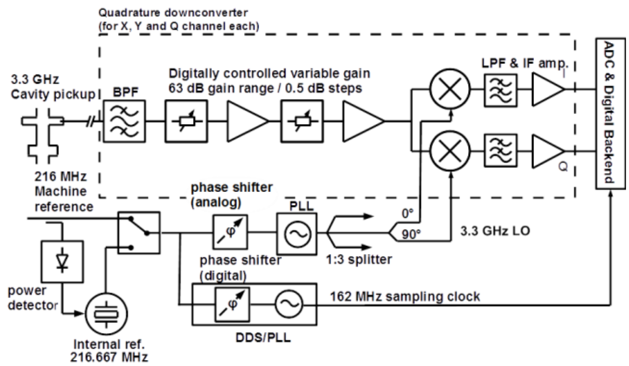

Figure 1: Simplified downconverter block diagram (one channel).

An input band pass filter selects the cavity signal components around 3.3GHz. The filter is followed by a programmable gain section.

The quadrature downconverter operates with a programmable LO frequency of ~3.3GHz. The LO is locked to a machine reference signal that has a stable phase relative to the electron bunch. This signal is 216.666 MHz at EXFEL and 142.8 MHz for SwissFEL.

In order to provide a bunch-synchronous sampling a second PLL is synthesizing the ADC clock signal of ~160 MHz from the machine reference signal.

This reference signal may be replaced by that of an internal crystal oscillator running at the same nominal frequency. This internal oscillator is automatically switched on in case the external clock fails, detected by measuring the *reference* signal power, or it can be switched on manually.

When the local reference crystal oscillator is activated the BPM system is not synchronized to the beam arrival any more. This "emergency" mode was implemented in order to still be able to get approximate beam position readings (with less accuracy compared to the nominal mode) when the reference clock distribution in the accelerator fails.

A programmable phase shifter for the LO is used to keep the reference cavity signal constant at 45 degrees by a feedback algorithm implemented on an FPGA on the GPAC. The phase shifter can also be set manually, which is used to measure and calibrate the I/Q imbalances of the downconverter.

The BPM electronics automatically adjusts the ADC sampling phase so that one sample is always at the top of the RFFE output pulse [3]. An FPGA on the GPAC board controls a direct digital synthesizer (DDS) on the RFFE that performs both phase shifting and frequency division prior to the final multiplication up to the sampling frequency.

SwissFEL and EXFEL RFFEs

SwissFEL linac and transfer line BPM systems use essentially the same RFFE boards. The SwissFEL prototype systems presently under test at the SwissFEL Test Injector Facility (SITF) only differ from the E-XFEL RFFE in the choice of filter parameters in the baseband section in order to accommodate for the lower loaded-Q.

The SwissFEL undulator BPM systems is planned to use dual-resonator high-Q cavities (Q_L~1000) with ~ 4.8 GHz operating frequency. High-Q cavities are appropriate here because the undulator section operates in single bunch mode only.

GAIN AND I/Q IMBALANCE CALIBRATION

As in every analog system the RFFE electronics shows systematic imperfections in both the downconverter section (I/Q imbalance) and the variable attenuator (DSA) section (attenuator setting inaccuracies). Both imperfections are suppressed by applying correction look-up tables before the sampled data is entering the position and charge calculation algorithms on the GPAC FPGAs.

The look-up tables are generated by a laboratory set-up in the first place. Because of differences between a real machine environment and the laboratory set-up a beam-based post calibration is planned [6].

Pre-calibration is performed for the following parameters:

- The I/Q gain and phase imbalance of the analog downconverter
- The gain setting of the digital step attenuators
- The overall gain factors relating vector magnitudes (in digits) to position (in mm) and charge (in pC)

In the following, we will describe a preliminary pre-calibration procedure that we so far have used for the E-XFEL pre-series electronics installed at FLASH1/2 and PSI, as well as possible improvements for the final calibration scheme to be used for the E-XFEL series version of the CBPM system.

Calibration Set-Up

The basics of the set-up used for the RFFE pre-calibration in the laboratory can be seen in Figure 2.

The synthetic pickup RF pulses are generated by an RF signal generator with wideband modulation capabilities. It is modulated by a baseband pulse resembling an exponential decay with a decay time constant of 7ns. This simulates a cavity loaded quality factor (loaded-Q) of 70.

The RF signal is then split equally into 3 parts and (after isolation) connected to the RFFE RF inputs.

A measurement Windows PC controls the MBU crate via LAN and the signal generator via GPIB.

The calibration procedure is implemented into MATLAB software. The control of RFFE and MBU functionality is provided by EPICS.

After pre-calibration all calibration data are stored into an EEPROM located on the RFFE board.

ISBN 978-3-95450-141-0

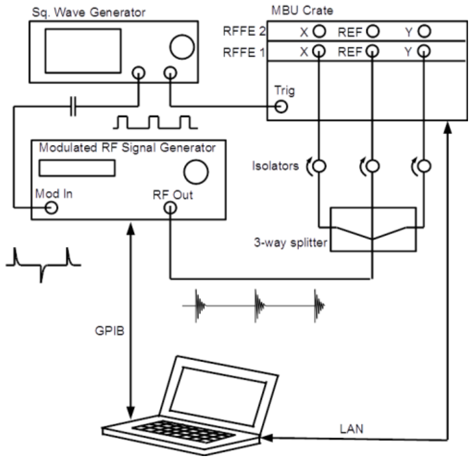

Figure 2: Principle of Laboratory Calibration Set-Up.

Downconverter Imbalance Calibration

The laboratory pre-calibration starts with measuring and the I/Q imbalance of the downconverter. During this step the signal phase is swept by stepping the internal phase shifter over a range >360 degrees in steps of ~10 degrees. The phase angles and the magnitudes of the resulting baseband signals are recorded. Finally a look-up table (1 degree steps) is generated that corrects for the imbalance. Angle values in between the steps are linearly interpolated.

Attenuator Calibration

After the I/Q imbalance has been corrected the digital step attenuators (DSA) that are determine the overall gain of the RFFE input channels are calibrated. The goal is to precisely know the actual gain setting of the RFFE channels. Ideally no change in charge or position reading should be seen after the RFFE gain has been changed.

During attenuator calibration the previously determined I/Q-imbalance correction is turned on. The DSA is swept from 0dB to 50dB in 1dB steps. At each step the magnitude of the IF vector is recorded. By comparing the measured attenuation to the nominal attenuator setting a correction (calibration) table is generated.

The signal phase change at each attenuator step is also measured and recorded and stored in a calibration table, which is important for the so-called beam angle correction explained below.

Overall Scale Factor Calibration

The final calibration step is to determine additional three numbers that relate the vector signal amplitudes (in digits) to position (in mm) and charge (in pC).

This step uses a signal generator setting of known RF pulse amplitude at the RFFE inputs. This amplitude has previously been determined using a fast oscilloscope. The scale factors are determined to show a charge and position that would result from a nominal cavity pickup with nominal sensitivities for reference and position channels with the same RF output signal amplitude as the synthetic pulse.

Beam Based Calibration

Beam tests at FLASH2 have shown that absolute position and charge readings are typically within a few percent of their true values. Beam based calibration methods may be used to increase absolute precision [6].

SIGNAL PROCESSING

Presently, the position calculation algorithm only uses a single sample at the top of the RFFE output signal pulse, as well as some samples of the baseline before the pulse to suppress common mode variations of the signal baseline. RF and sampling phase are stabilized using algorithms briefly described in [3]. Phase and amplitude drifts of the reference signal or the beam arrival time are compensated automatically via digital feedbacks of the GPAC.

From the raw ADC data the vector magnitudes and vector phases are calculated. The vector magnitudes are then multiplied each by a value stored in the I/Q calibration table. Finally, the resulting vector magnitude information is used to calculate the beam charge and the beam positions in x and y direction.

BEAM TEST RESULTS

I/Q Imbalance Calibration

Under nominal operation the BPM is synchronized to the beam arrival. The relative vector angle between reference and position channel is constant. However, before commissioning this relative angle is not known due to differences in pickup cable length, which cannot practically be avoided. Furthermore, the digitally programmable attenuators used on the RFFE have a phase delay that depends upon the programmed attenuation value. Therefore, the relative phase angles between the RFFE channels may change after a different charge or position range has been selected by reprogramming the attenuators. Relative phase shifts result in amplitude errors due to phase and amplitude imbalance occurring in the analog downconverter. In order to minimize this effect the imbalance (I/Q imbalance) is compensated using a look-up table. This table is initially generated by pre-calibration. The final calibration, if required, is done beam-based.

The pre-calibration using the laboratory calibration set-up is tested with beam by turning the LO phase feedback loop off and sweeping the LO phase of the downconverters over 360° using the internal LO phase shifter. Relating the charge reading to a second charge reading from a second BPM the deviation can be evaluated. Figure 3 shows an example of a beam measurement where the charge of one BPM is seen to depend upon the actual LO phase angle.

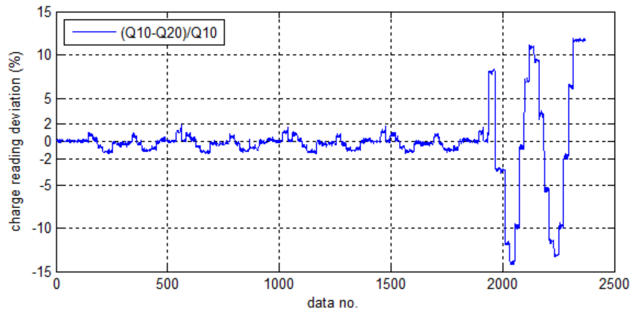

Figure 3: Pre-Calibration imbalance correction (calibration turned off for data points 1900 and higher).

As can be seen the pre-calibration is good to roughly ±1%. The final accuracy can be reached after application of beam based calibration procedures [6].

Attenuator Pre-Calibration

If the charge readings of several BPMs are compared while the gain of one BPM is stepped one ideally sees no steps in the charge readings.

After pre-calibration there is still a charge reading depending on the gain setting (Figure 4). This remaining difference may be reduced further beam-based.

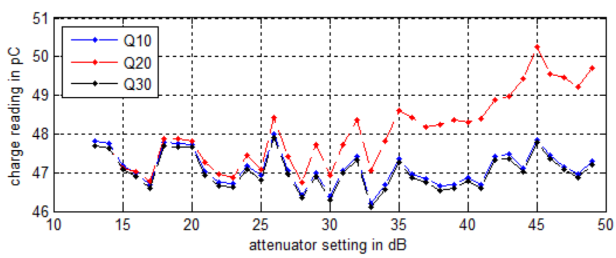

Figure 4: Charge Reading versus attenuator setting. The attenuator of BPM20 (red lines) was stepped.

Electronics Linearity

Since position and reference channel are identical (except an extra attenuator at the input of the reference channel), charge measurements were used to assess the nonlinearity of the RFFE input channels.

The reference channel linearity is measured in the following way: At a given beam charge the reference attenuator of the BPM under test (TBPM) is set such that its reference channel nearly saturates. A second BPM, the reference BPM (RBPM) has its reference attenuator set to a value about 20dB higher than that of the TBPM. It is assumed that the RBPM with its low amplitude does operate within its linear range, since nonlinear deviations are typically expected to occur at high signal amplitudes. Figure 5 shows beam measurements using 4 BPMs at SITF. BPM 40 (green curve in Figure 5 is the reference BPM).

Plotting the charge reading of the test BPM against the reading of the reference BPM now shows any nonlinear behaviour. However, Figure 6 suggests a good linearity over the full signal range with deviations from the linear fit being smaller than ±1%.

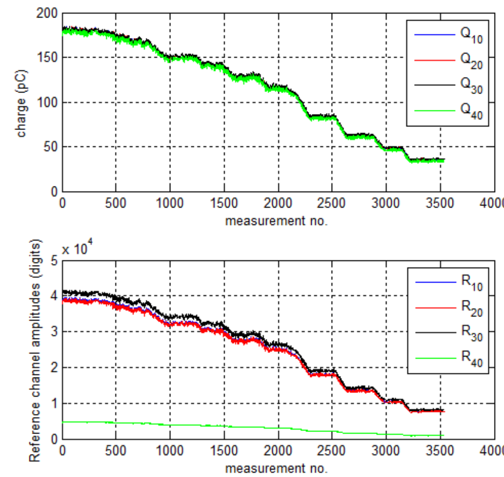

Figure 5: Linearity Measurement (charge readings and IF output amplitudes).

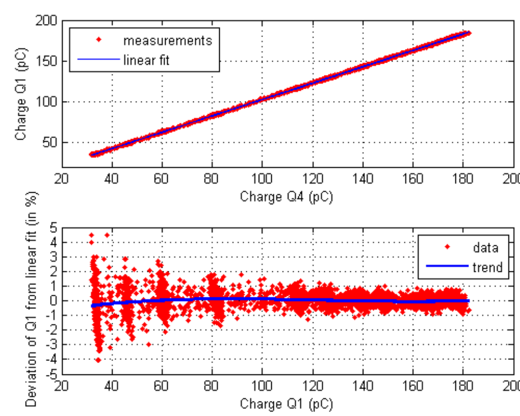

Figure 6: Deviation of the charge reading from linear fit.

Position Resolution

Position resolution is measured using the method described in [3].

The single bunch position resolution requirement for EXFEL undulator BPM systems is 1µm rms within a measurement range of ±500µm and within the charge range 100pC to 1nC.

Figure 7 shows the results of resolution measurements taken at SITF and at three different beam charges: 30pC, 100pC and 200pC. Higher charges were not available. All measurements used a full-scale position range of ±600µm. Position resolution is better than 1µm rms for all charges above 30pC and at all beam offset positions within this measurement range.

Similar measurements using EXFEL undulator BPMs at higher beam charges have been undertaken at FLASH1 (DESY, Hamburg) and are reported in [1].

ISBN 978-3-95450-141-0

Results generally agree in the fact that resolution requirements of EXFEL and FLASH2 BPM electronics are met or exceeded by the present PSI cavity BPM system.

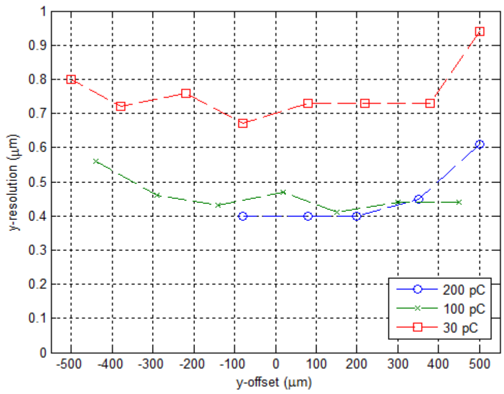

Figure 7: Measured position resolution for a ±600µm measurement range at different beam charges (EXFEL undulator BPMs).

It is worth noting that the position resolution is predictable by theory quite precisely. In contrast to this almost all other important BPM parameters, as for example temperature drift, linearity, or final accuracy, are far less predictable. An isolated view on the BPM resolution alone is therefore not considered adequate to characterize the performance of a BPM system.

Positon Temperature Drift (Lab Measurement)

The temperature drift of the ratio of position to reference channel amplitude (=position drift) has been measured under controlled laboratory environment using a similar set-up as seen in Figure 2. The room temperature was raised slowly over several degrees. The position reading and temperature of a nearby and not actively stabilized RFFE were logged and plotted against each other.

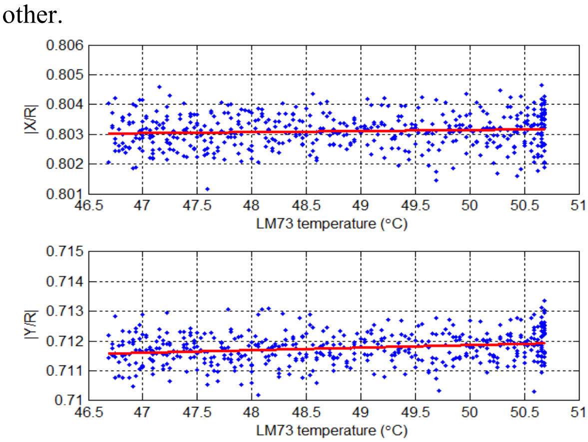

Figure 8: Position Reading (internal units) vs. Temperature.

It is found that the position reading drifted less than 0.01% per degree of ambient temperature change. At the upper precision range demanded by EXFEL this would result in a position drift of 50nm per °C. Further drift tests are pending.

CONCLUSION

We described the new cavity BPM electronics that is presently installed at FLASH2, which is a pre-series of the E-XFEL version. A set-up used to pre-calibrate the BPM electronics in the laboratory has been described. Finally some beam measurement results taken at the SwissFEL Injector test facility were presented. The results indicate adequate position resolution, in agreement with earlier measurements, good electronics linearity and temperature stability.

The laboratory pre-calibration method presently in use is able to bring the absolute accuracy to within a few percent. Possible improvements of pre-calibration results are discussed in [6].

In order to improve the calibration beyond what is already reached by laboratory based pre-calibration it is suggested to use beam-based procedures at commissioning of the BPM system.

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