BEAM-BASED CALIBRATION AND PERFORMANCE OPTIMIZATION OF CAVITY BPMS FOR SwissFEL, E-XFEL AND FLASH2*

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Abstract

SwissFEL, the European XFEL (E-XFEL) and FLASH2 all use dual-resonator cavity beam position monitors (CBPMs) [1,2,3]. The CBPM electronics that is built by PSI has a larger number of calibration parameters that need to be determined in order to maximize the CBPM system performance. Beam measurements with the BPM electronics have been made in BPM test areas at the SwissFEL test injector and FLASH, as well as at FLASH2 where 17 E-XFEL type CBPMs have recently been installed in the undulator intersections. The CBPMs are pre-calibrated in the lab using an automated test and calibration system [4], and then the final calibration is done with beam. This report discusses beam-based methods to optimize the system performance by improving the pre-beam system calibration as well as the mechanical alignment of the BPM pickup position and angle.

PICKUPS

CBPM pickups with two resonators are the standard choice for measuring and stabilizing the beam orbit with highest resolution and lowest drift in the undulators of free electron lasers (FELs). The reference resonator measures the bunch charge, while the position resonator provides the product of bunch position and charge. The bunch position is thus obtained by normalizing position to reference resonator amplitude for the relevant monopole (reference) and dipole (position) modes, with a scaling factor that depends on the usually variable attenuation of the RF front-end (RFFE) input channels. All of the above mentioned FELs have CBPMs with cylindrical resonators and mode-selective couplers in the position resonator, where the frequencies of position and reference cavity modes are identical, thus minimizing the impact of frequency-dependent gain drift on the position readings.

Since the above mentioned FELs can also have several bunches with rather short bunch spacing (222ns for E-XFEL and FLASH, 28ns for SwissFEL), comparatively low loaded quality factors Q_L were chosen (see Table 1). This minimizes bunch-to-bunch crosstalk and keeps the effort and latency of the digital signal processing low, as required for the E-XFEL Intra Bunch Train Feedback (IBFB) [5]. Only in the SwissFEL undulators that have single bunches with 100Hz repetition rate, the CBPM pickups have a higher Q of ~1000 [6]. All E-XFEL CBPMs and the SwissFEL injector and linac CBPMs have stainless steel pickups with ~3.3GHz nominal frequency, which is safely below the cut-off frequency of the different beam pipe diameters. This allows using the same low-Q CBPM electronics for all machines [4,7]. In the following, the pickups will be named according to their beam pipe aperture, where e.g. CBPM16 is the 16mm aperture pickup of the SwissFEL linac.

Table 1: Overview of CBPM Pickups

	F [GHz]	Q_L	Aper-ture [mm]	Length [mm]
E-XFEL Transfer	3.300	70	40.5	255
E-XFEL/FLASH2 Undulators	3.300	70	10	100
SwissFEL Linac and Injector	3.284	40	38	255
	3.284	40	16	100
SwissFEL Undul.	4.855	1000	8	100

The E-XFEL CBPM10 and CBPM40 pickups developed by DESY have already been produced. First beam in the E-XFEL injector is expected spring 2015, first beam in the main linac end 2016. For the SwissFEL BPM pickups designed by PSI, the CBPM38 production is finished, while the CBPM16 pickups are ready for series production that will start shortly. Prototypes of the BPM8 pickup have recently been tested successfully with beam [6], where we have made a 3.3GHz stainless steel version with Q_L~200 and a 4.8GHz copper-steel hybrid version with Q_L~1000. Until recently the steel version had been the baseline since it is simpler and could have been operated with the standard 3.3GHz electronics with minor changes. However, after successful fabrication and test of the 4.8GHz pickup we made it the baseline version due to its higher expected resolution both at high charge (due to higher Q) and very low charge (due to higher sensitivity that improves with higher frequency). First beam in the SwissFEL injector is scheduled for end 2015, first main linac beam for end 2016.

Presently, three E-XFEL CBPM10 and three CBPM40 pickups are installed at the SwissFEL Injector Test Facility SITF at PSI, one more CBPM40 and three CBPM10 at FLASH1. At SITF, also one SwissFEL CBPM38, one CBPM16 and two CBPM8 (steel and copper version) are installed, see Figure 1. While these pickups are only intended for testing (with stripline and button BPMs used as "working horses" for normal machine operation), the recently installed 17 CBPM10 systems in the FLASH2 undulator intersections are needed for machine operation, but are also still part time

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available for tests since FLASH2 is still in the commissioning phase and does not yet have users.

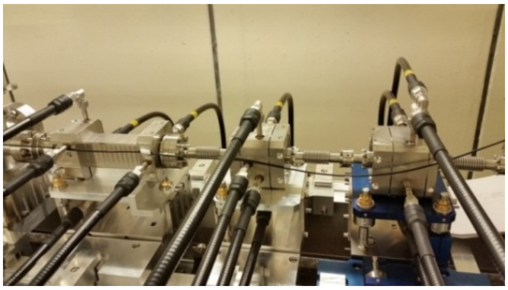

Figure 1: SwissFEL CBPM38 (left), CBPM8 with Q_L=1000 (middle) and CBPM8 with Q_L=200 (right).

The horizontal (X) and vertical (Y) position of two CBPM10 at SITF and all four CBPMs at FLASH1 can be adjusted within a range of > ±1mm via motorized 2D mover stages with sub-micron resolution encoders, while all other CBPM pickups at SITF and FLASH1 require manual X and Y position measurement and adjustment.

The pickup angles dX/dS, dY/dS and dY/dX (where S is the longitudinal coordinate) are also measured and adjusted manually for all pickups.

ELECTRONICS

The CBPM electronics for the E-XFEL, FLASH2 and SwissFEL low-Q pickups has an RFFE (see Figure 2) that mixes the 3.3GHz ringing signals of the pickup down to baseband. The bandpass and variable gain input stage of the RFFE reference and position input channels (that have a symmetric design) is followed by an IQ mixer and a lowpass/bandpass stage. The on-board local oscillator (LO) for the I/Q mixer is normally synchronized to an external bunch-synchronous reference clock, with an internal backup oscillator that automatically takes over when the external clock fails. The I and Q output signal pulses of the RFFE have some 10ns length and are sampled by high-speed 16-bit ADCs with differential inputs. The bunch-synchronous ADC clock is also generated by the RFFE. The ADC output signals are processed by an FPGA board that provides interfaces to control, timing, feedback and machine protection systems.

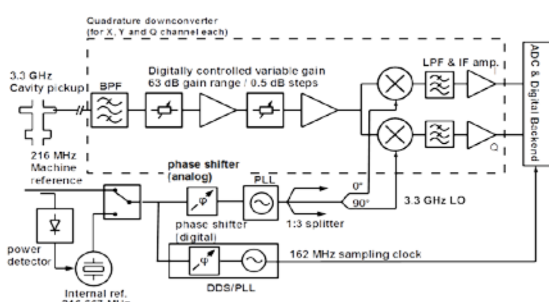

Figure 2: Simplified schematics of low-Q CBPM RFFE electronics, showing only one of its three input channels.

The FPGA board also controls various ADC and RFFE parameters (LO and ADC clock frequency and phase, temperature stabilization set points, ...) and stabilizes the IQ signal phases (via LO phase shifter) and ADC clock phase (via DDS-phase shifter) by FPGA-based digital feedback loops. An optional automatic range control (ARC) adapts the attenuators of the RFFE to varying input signal levels, thus minimizing ADC-related position and charge noise.

Recently, electronics for 17 CBPMs have been installed at FLASH2, a new soft X-ray undulator line at the DESY FLASH FEL facility. In addition, also the four FLASH1 CBPMs and all 3.3GHz CBPMs at SITF are equipped with the same electronics, except for the SwissFEL low-Q RFFEs at SITF where the output (IF) stage has been slightly modified (by soldering different filter components) in order to reduce the bunch-to-bunch crosstalk for the very short bunch spacing of 28ns.

Figure 3: Cavity BPM electronics for two BPMs. Two RFFEs (top) and the FPGA carrier board with ADC mezzanines (bottom) are inserted into a customized crate from the front side. Power supply module and boards with SFP+ transceivers etc. are plugged in from the rear side.

BEAM BASED CALIBRATION AND DIGITAL SIGNAL PROCESSING

The CBPM system has a number of parameters that need to be calibrated in order to obtain accurate data in physical units for beam position and charge. Our general strategy is to determine these parameters first with lab equipment as good as possible with reasonable effort, and then to make a more accurate beam-based calibration where needed. For the beam-based calibration, one can compare the BPM readings either with other monitors or encoders of motorized BPM pickup movers, or with other BPMs, utilizing the fact that the information provided by the BPM system is usually redundant, where the position and charge at the location of one BPM (or the derivative or other functions of these quantities) can be predicted using the other BPMs or monitors. This allows determining calibration parameters by tuning them such that the difference between prediction and measurement is minimized.

Absolute Position Calibration

In contrast to button or stripline BPMs, CBPMs have a larger uncertainty of the absolute scaling factors that convert signal amplitudes to millimeters. While the scaling factor for button and stripline BPMs can usually be determined entirely from the pickup geometry, the factor for the CBPM position depends on the overall gain and attenuation of the whole signal path, from pickup resonator via RF feedthrough and cables to RFFE and ADC. Any unknown loss on this path changes the scaling factor, thus it can usually just be pre-determined by lab measurement of BPM components with a limited accuracy in the order of typically ~10%, depending on system design, measurement tools and methods.

For the SwissFEL undulator CBPMs, the position scaling factors can be determined beam-based via motorized BPM pickup movers and encoders for all CBPMs. In the SwissFEL injector, linac and transfer lines, as well as in the whole E-XFEL, the CBPMs do not have motorized movers for cost reasons (except one CBPM10 in E-XFEL). The scaling factors for these BPMs will be determined using beam optics models and cross-comparisons with screens, wire scanner monitors, or other BPMs with motorized movers.

Absolute Charge Calibration

Both in E-XFEL and SwissFEL, the CBPMs will also be used as charge monitors, since they can measure relative charge variations with high resolution of typically 0.05% at higher bunch charges. The absolute calibration of the BPM charge scaling factor will be done by comparing the BPM readings with dedicated charge monitors that have a more accurate absolute calibration, e.g. toroids, where care must be taken that the beam loss between BPM and toroid during calibration is negligible.

Digital Signal Processing

Figure 4 shows show the algorithm that calculates beam position (X and Y) and charge (Q) from the ADC raw values. In order to achieve a desired overall IBFB feedback loop latency of ~1µs or less, the algorithm was implemented in VHDL on the BPM FPGA board. An FPGA-based feedback automatically tunes the ADC clock phase such that the RFFE output pulses always have one sample exactly at their top. This sample is then used to calculate the beam position and charge, using some samples before the pulse to perform baseline subtraction and thus eliminate any low-frequent noise. An optimal algorithm that uses all samples would only improve the noise by ~30% and was thus not (yet) implemented. The ADC phase feedback shifts the clock phases of reference and position signals together using a DDS clock generator on the RFFE, e.g. for compensation of beam arrival time or machine reference clock drifts. The alignment of the ADC sampling phases relative to each other is only done once, using programmable delay shifters on the ADC board. After determining the signal amplitudes of the I and Q channels, Cartesian-to-polar conversion is performed. The resulting amplitude and phase (A,φ) for position and reference channel have systematic "IQ imbalance" errors, since the gains of I and Q channel are not exactly identical and since their phase difference is not exactly 90°. This IQ amplitude and phase imbalance is corrected digitally by the FPGA, using a lookup table obtained from an automated lab calibration system [4] which also determines the attenuation of the variable attenuators in the RFFE. Over their 63dB range they can be changed in steps of 0.5dB, where small deviations of nominal and real attenuation cause small systematic measurement errors (i.e. steps) of X, Y and Q readings when the attenuators are changed (see below).

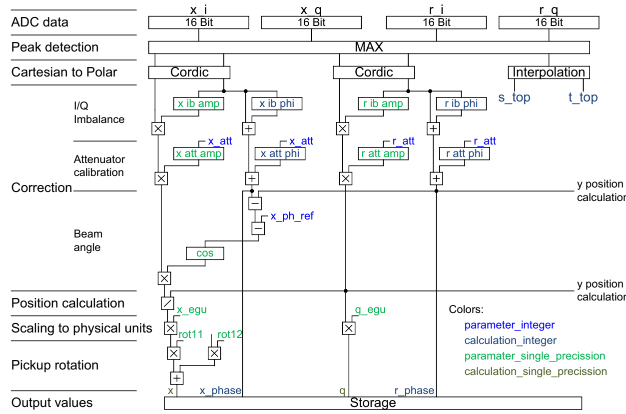

Figure 4: Simplified data flow of the CBPM signal processing algorithm.

Varying the attenuation also causes a shift of the phase delay between RFFE input and output. This is also calibrated in the lab and corrected by the FPGA firmware. The resulting IQ angle is thus attenuation-independent and can be used for the so-called beam angle correction. This correction digitally suppresses a systematic measurement error of the beam position, caused by the undesired beam angle signal, which is a position cavity signal component caused by a relative angle dX/dS or dY/dS between beam and longitudinal pickup axis. The dominant cause of this angle signal is the mechanical misalignment of the pickup.

Without digital angle signal correction, the 2-dimensional amplitude vectors (I_x,Q_x) and (I_y,Q_y) are the sum of a vector proportional to the product of beam position and charge, and of an orthogonal vector proportional to the product of beam angle and charge, e.g. for the X plane $(I_x,Q_x) = (I_{x\_pos},Q_{x\_pos}) + (I_{x\_ang},Q_{x\_ang})$. The angle signal sensitivities for the different pickups are shown Table 2, where the unit µm/mrad means that a pickup angle misalignment of 1mrad results in a beam angle signal as large as the (orthogonal) beam offset signal would be for 1 µm.

For large beam offsets, the beam angle signal usually causes a negligible error of the beam position. However, when moving the beam position from larger positive values through zero, without beam angle correction the calculated beam position would not reach zero, but converge from larger values to e.g. +16µm for an 1mrad misalignment of CBPM40, and then jump to -16µm when the beam crosses the pickup axis. In order to avoid this, the FPGA algorithm e.g. for X projects (I_x,Q_x) to a unit vector that is orthogonal to the beam angle signal (and parallel to the beam position signal) before performing the Cartesian-to-polar conversion (see Figure 4). This unit

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vector is obtained by rotating the IQ vector for the reference channel by a fixed angle. This angle is determined with beam, using the fact that the unit vector and (I_x,Q_x) are (nearly) parallel for large beam offsets. Thanks to the above mentioned correction of the attenuation-dependent IQ phase, the unit vector stays orthogonal to the beam angle signal for any attenuation.

Table 2: CBPM pickup angle sensitivities, expected alignment errors after beam-based mechanical realignment (SwissFEL: For shimming-based / screw-based adjustment), and resulting beam angle signal.

	Angle Sensi-tivity [µm/ mrad]	Angle Alignment Error [mrad]	Angle Signal [µm]
E-XFEL CBPM10	1.0	<0.2	0.2
E-XFEL CBPM40	16	<0.2	3.2
SwissFEL CBPM8	5.2	0.1 / 0.02	0.5 / 0.1
SwissFEL CBPM16	4.3	0.1 / 0.02	0.4 / 0.1
SwissFEL CBPM38	15.5	0.04 / 0.01	0.6 / 0.16

Beam Based Pickup Angle and Offset Calibration

The X and Y offset of the CBPM pickups will be calibrated beam-based using well-established beam based techniques like dispersion free steering or ballistic methods, where only measurements of relative beam movements are required to determine the offset of the CBPM. For the mechanical offset of the pickup, laser-tracker based alignment allows reaching offsets well below 100µm with respect to the nominal beam trajectory, where the beam-based alignment then allows to verify the initial alignment and correct it where needed.

However, despite digital beam angle error correction we intend to perform beam-based correction of the pickup angle misalignment in order to improve the initial laser-tracker based alignment, aiming to reduce the beam angle signal to an equivalent <1µm beam offset (see Table 2). This makes sure that, even without perfect calibration e.g. of the attenuation-dependent IQ phase shifts, the remaining angle-induced beam position error is negligible compared to the sub-micron BPM position noise and drift requirements for FEL undulators and IBFB CBPMs [1,2].

When the X beam position moves from large positive values through zero and then to large negative values, φ_x changes by 180°. Figure 5 shows a plot of φ_x vs. X, measured with beam for three CBPM10 installed at SITF, where φ_x was normalized to 0° at X=0mm. At φ_x=±45°, the two orthogonal vectors (I_{x_pos},Q_{x_pos}) and (I_{x_ang},Q_{x_ang}) have the same length, thus the beam angle is simply the beam position (calculated with active angle correction) where φ_{x}=45°, divided by the beam angle sensitivity. While the first and third pickup have mechanical misalignments of about 2mrad and 3mrad, the second BPM10 pickup has a much larger value of about 22mrad. For SwissFEL and E-XFEL, the angles of the CBPM pickups will be measured with beam, and then corrected manually. For SwissFEL, most BPMs have fixed supports where pickup angle and positions are adjusted via shimming plates. Some SwissFEL BPMs are equipped with a support where angle and offset can be adjusted via differential screws (see Figure 1). Table 2 shows the expected angle alignment errors and resulting angle signal amplitudes after beam-based calibration and realignment.

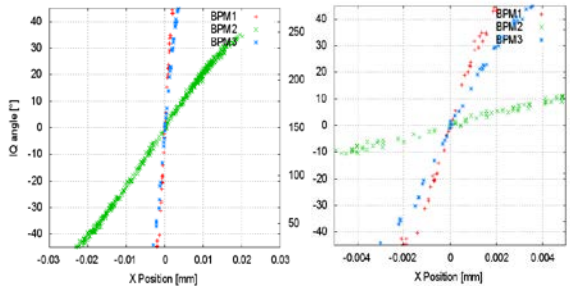

Figure 5: Measurement of IQ vector phase vs. beam position (same data with different X scales).

Beam Based Attenuator Calibration

In our baseline concept, we plan to operate E-XFEL and SwissFEL CBPMs with fixed attenuator settings for each accelerator operation mode, e.g. 10pC short bunch and 200pC standard SwissFEL operation mode. A coarse lab-based calibration of IQ imbalance and attenuators for each operation mode would already be sufficient, since the beam arrival time jitter is extremely low, and the IQ signal phase is nearly constant due to the LO phase feedback. Therefore, the beam-based calibration is only needed to determine and correct the absolute scaling factors for charge and position (for each operation mode), the pickup offsets and angles, as well as the angle between reference and position IQ vector as required for the above mentioned angle signal suppression (and to determine the sign of the beam position).

However, for 1st beam commissioning or accelerator test shifts where large beam position and charge variations may occur, it would be useful to use many or all of the 125 attenuator settings of each RFFE channel, with an automated range control (ARC) that adjusts the attenuators automatically such that the ADC signal levels are reasonably high but still do not saturate, thus minimizing ADC-related position and charge noise automatically for any beam position and charge. After implementing a first very simple version of such an ARC on the FPGA board, we have made a coarse calibration of the attenuators in the lab with a pulsed signal generator, using the signal generator set value for calibration. Then we improved the lab-based calibration with beam, using a least-square fit of the attenuator correction factors for the different attenuator settings, such that the errors (steps) caused by attenuator changes are minimized. At first, tests at FLASH with nearly constant bunch charge were performed. During the measurement, the ARC changed the position channel attenuators many times due to larger beam movements, e.g. for Y between 7 and 14dB. The reference channel attenuators were not changed due to the

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nearly constant charge. With the coarse lab-based calibration, the Y position RMS error (calculated by correlating three CBPMs) was about 650nm RMS, which is about 3 times larger than without ARC. After beam-based calibration, the noise with and without active ARC was nearly identical and about 220nm RMS.

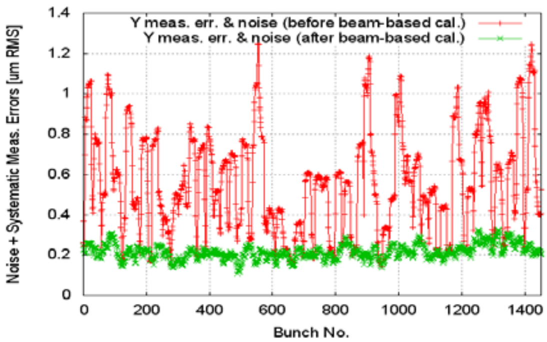

Figure 6: Floating average of the Y RMS measurement error (noise plus systematic errors due to switching attenuators etc). of FLASH CBPMs vs. bunch number before and after beam-based calibration of attenuators, calculated by correlating the readings of three CBPM10.

As mentioned above, the phase delay of the attenuators and thus the angle of the (I,Q) vector of the RFFE output signals depends on their attenuation. This also causes systematic attenuation-dependent errors when the IQ imbalance is not perfectly calibrated. Beam tests have shown that with our present lab-based calibration, we still have ~1% IQ imbalance [4]. It should however be noted that the beam-based calibration of the scaling factors we did for each attenuator setting does not only correct the attenuation, but also any remaining IQ imbalance at the same time.

The left plot in Figure 7 shows the charge ratio of two adjacent CBPM10 before (red) and after beam-based calibration, measured at SITF while the bunch charge was ramped down from 180pC to 75pC. After beam-based calibration, the previous errors of >1% were reduced to a relative charge noise of ~0.05%, that we also measure at constant charge and fixed attenuators. The right plot in Figure 7 shows the reduction of the position measurement error due to the beam-based calibration. In contrast to the measurement above at FLASH, the beam position at SITF was affected not only by the changing attenuators in the position channels of the RFFE, but also by the changing reference channel attenuators. However, also here the beam-based attenuator calibration resulted in a strong reduction of attenuator-dependent systematic errors from more than 2000nm RMS to 670nm RMS, using a measurement range of about ±400µm.

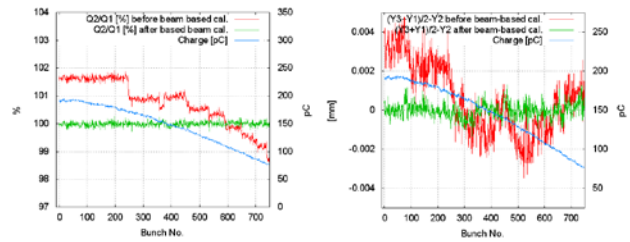

Figure 7: Left: Charge ratio of adjacent CBPM10 before and after beam-based calibration. Right: Difference between predicted and measured position at a CBPM10 at SITF, using adjacent CBPM10 for the prediction, before (red) and after (green) beam-based calibration.

SUMMARY AND OUTLOOK

The status, calibration and signal processing concept, and first beam-based calibration results for the low-Q CBPM systems for E-XFEL, FLASH2 and SwissFEL were presented. First beam tests have shown that our lab-based calibration of the CBPM electronics can be significantly improved with beam, making the switching of the RFFE attenuators basically invisible. Although this is not necessary for the baseline FEL operation modes where the attenuators will normally have fixed values, the improved calibration enhances the system performance for non-standard modes e.g. during 1st beam commissioning or accelerator test shifts.

We now plan to improve our present coarse lab-based calibration, e.g. by splitting the RF generator signals to several CBPM electronics, and then calibrating the RFFE attenuation and IQ imbalance by correlating readings of several CBPM electronics like we did for the beam-based calibration. Combined with an optimization of the pulse shape and spectrum of our lab signal pulse generator, we are aiming to further minimize the difference between lab- and beam-based calibration results.

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