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FIRST BEAM COMMISSIONING EXPERIENCE WITH THE SwissFEL CAVITY BPM SYSTEM

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Abstract

SwissFEL is a free electron laser facility designed to produce FEL radiation at wavelengths from 0.1 to 7 nm. The beam commissioning of its hard X-ray undulator line ("Aramis") started 10/2016, and first lasing was observed in 12/2016. Presently, a 2nd undulator line ("Athos") for soft X-rays is being constructed, with 1st beam scheduled for mid-2019. In the injector, linac and Aramis beam transfer lines, 95 low-Q cavity BPMs operating at 3.3 GHz are used that were designed to support the future two-bunch operation mode with 28 ns bunch spacing and 100 Hz repetition rate. The Aramis (and future Athos) undulator lines will only be operated with single bunches by means of a fast beam distribution kicker system, and are thus equipped with high-Q cavity BPMs operating at 4.9 GHz. The BPMs are not only used for beam trajectory optimization, but also for beam energy measurements (using standard cavity BPMs in the bunch compressors and beam dumps), beam charge and transmission measurements, or improvement of the performance of other monitors like wire scanners for profile measurement. This paper will report about the first operation experience with the BPM system, including a performance comparison of low-Q and high-Q BPMs.

INTRODUCTION

BPM Pickups

Table 1 gives an overview of the number and type of BPMs (119 overall) that are presently operational in SwissFEL. CBPM38 low-Q pickups are only used at a few locations where their large aperture is needed (1st bunch compressor, beam distribution area, beam dumps). Undulator intersections are equipped with high-Q CBPM8 pickups, while low-Q CBPM16 pickups are used everywhere else.

Table 1: SwissFEL BPM Types and Quantities

	CBPM38	**CBPM16**	**CBPM8**
Quantity	7	96	24
Usage	Linac, Transfer Lines		Undulators
Aperture	38 mm	16 mm	8 mm
Length	255 mm	100 mm	
#Bunches/ Train	1-3		1
Bunch Spacing	28 ns		10 ms
Frequency	3.2844 GHz		4.9266 GHz
Q_L	40		1000

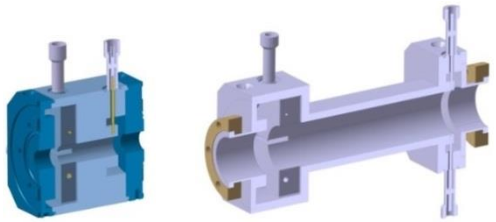

Figure 1: SwissFEL CBPM16 pickup (left) and CBPM38 pickup (right).

CBPM38 and CBPM16 pickups (shown in Figure 1 and Figure 2) differ in aperture and length, but were designed to deliver (nearly) the same sensitivity and RF parameters [1], thus providing similar performances.

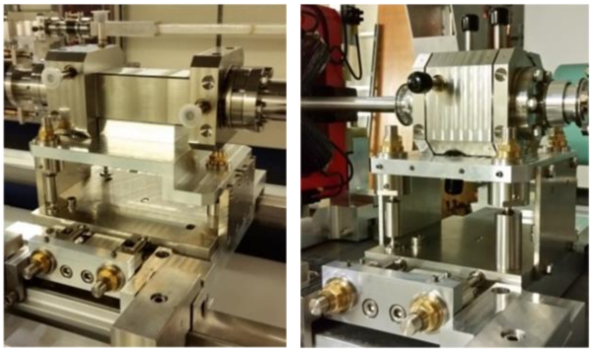

Figure 2: CBPM38 (left) and CBPM16 pickup (right) with manually adjustable supports.

Like the SwissFEL C-band accelerating structures, the BPM pickups (incl. CBPM8) have no tuners but were precision-machined to the nominal frequency and other RF parameters. The achieved very small deviations [1] have negligible impact on the performance.

The position resonators of the pickups have two ports both for the horizontal (X) and vertical (Y) position signals. The two signals in each plane are added using an external RF combiner near the pickup that is connected with short flexible low-loss cables, thus improving the position resolution at low charge.

The relevant RF parameters of all pickups and long-range ½'' Sucofeed RF cables from pickups to the electronics racks (located outside the SwissFEL accelerator tunnel) were measured before 1st beam. The results were used to verify the quality of the system and do determine scaling factors for the conversion of raw signal amplitudes to charge and position in physical units already before 1st beam, followed by a more accurate beam-based calibration that is still in progress.

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BPM Electronics

Low-Q and high-Q BPMs have the same electronics, except for the RF front-ends (RFFEs), where the low-Q RFFEs perform IQ downconversion to baseband, (see Figure 3) while the high-Q RFFEs mix to an IF of ~134 MHz that is sampled by 16-bit ADCs at 161 MSPS and then digitally mixed to baseband (see Figure 4 and ref. [2]).

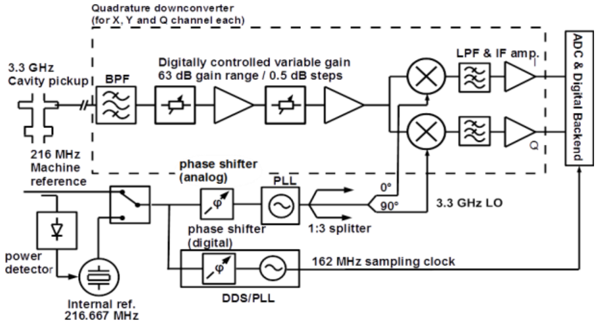

Figure 3: Simplified schematic of CBPM16/CBPM38 CBPM RFFE electronics, showing only one of its three input channels (one reference and two position signal channels).

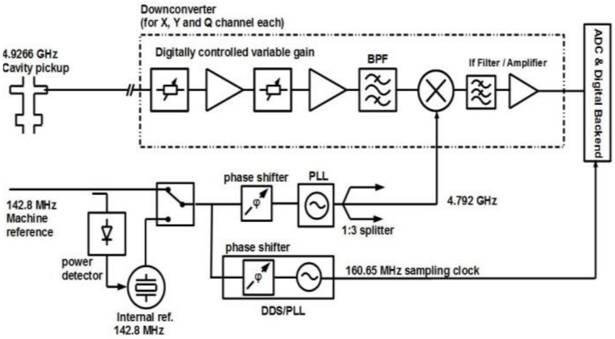

Figure 4: Simplified schematics of CBPM8 RFFE electronics, showing only one of its three input channels.

The BPM electronics consists of a customized crate called Modular BPM Unit (MBU, see Figure 5) [1][3] that contains two BPM-specific RFFEs, as well as a number of generic boards and modules, e.g. a modular power supply, or an FPGA carrier board (GPAC = Generic PSI ADC carrier) with two 6-channel 16-bit ADC mezzanine boards.

Figure 5: Modular BPM unit, with two cavity BPM RFFEs (top) and FPGA carrier board with two ADC mezzanines (bottom).

FPGA Board

The FPGA board version (called GPAC3) used in the SwissFEL MBUs is backward-compatible to the previous version (GPAC2) used in E-XFEL [3] regarding external interfaces and ADC mezzanine connectors. However, the GPAC3 uses newer FPGAs: Three Xilinx Artix7 200T and one Kintex7 160T, instead of three Virtex-5 FX70T and three Spartan-3A on the GPAC2. This reduced the production costs of the board by a factor 2 while providing a longer FPGA availability (last buy 2030 vs. 2022). Moreover, the GPAC3 is supported by the latest Xilinx FPGA design tools (Xilinx Vivado), while the development of the previous tool Xilinx ISE/EDK (used by GPAC2) was frozen by Xilinx in 2013.

The FPGA board PCB layout was changed from a 2+12+2 layer microvia stackup for GPAC2 (that is more sensitive to thermal stress during soldering) to a 16-layer through-hole design for GPAC3, which improved the production yield of soldered boards from typ. 87% to >98%. The GPAC3 uses Megtron-6 as PCB material, thus minimizing losses for the multi-gigabit links between the FPGAs and to the outside world (via SFP+ fiber optic transceivers) that can run at up to 10.3 Gbps for the soldered speed grades of the Kintex-7 (enabling e.g. 10G Ethernet) and 6.6 Gbps for the Artix-7 on the GPAC3, compared to 6.5 Gbps for the GPAC2.

Timing and Control System Integration

The SwissFEL BPM system uses fiber optic multi-gigabit links with optical multimode SFP+ transceivers as external high-speed interfaces. One transceiver is used as direct connection to the SwissFEL timing/event system that was developed by the company MicroResarch (like the older SLS system). The GPAC3 directly decodes the event data stream in one of its FPGAs using an event receiver implemented by PSI, thus saving the costs for a dedicated event receiver card (that is needed for most other SwissFEL systems).

The SwissFEL control system is based on EPICS and VME64x, while the SwissFEL BPM electronics is control system agnostic and can be interfaced to various control system hardware standards (e.g. uTCA used at E-XFEL). For SwissFEL, the data of all MBUs is collected by only seven VME64x CPU boards running EPICS, using additional boards with two quad SFP+ mezzanines in the VME64x crates to collect the data from the MBUs.

In contrast to the GPAC2 that only has two mezzanine connectors (e.g. for ADCs), the GPAC3 has a third (smaller) mezzanine connector for an optional microprocessor mezzanine (that could be equipped e.g. with a Xilinx Zynq SoC), which would allow to run EPICS directly on this mezzanine in the MBU (rather than using external CPU boards) if needed. Having the processor on a mezzanine rather than on the mainboard itself allows to add the processor only if needed and to choose different processors for different applications, thus saving costs and extending the board availability (where many processors tend to get obsolete earlier than FPGAs).

BEAM MEASUREMENTS

Scaling Factor Calibration

All SwissFEL BPM RFFEs have digital step attenuators (DSAs) with 63dB overall range in their position and charge channels that allow to achieve excellent resolution over a very wide bunch charge range. The DSAs as well as other RFFE parameters (e.g. IQ imbalance of the low-Q BPMs) are calibrated in the lab using test signal generators, where the FPGA then uses the calibration data (stored in an EEPROM on the RFFE) to calculate charge and beam positions. Combined with the previously mentioned pre-beam measurement of pickup and RF cable parameters, the SwissFEL BPM system was able to provide position and charge readings in physical units already at 1st beam with typ. 10-20% scaling factor error.

After steering the beam through the accelerator with negligible beam loss (verified e.g. via dedicated loss monitors), the charge readings of the BPMs were then calibrated using dedicated charge monitors (Bergoz ICTs).

Nearly all CBPM8 are mounted on motorized movers together with a quadrupole (in the undulator intersections), which allowed easy calibration of the position scaling factors via the very accurate mover encoders. In contrast, only two CBPM38 (in bunch compressor BC1) and two CBPM16 (in BC2) are mounted on motorized movers (that move the complete bunch compressor with BPMs, 2rd and 3rd bending magnet, and beam pipe). Thus, we used these movers to determine the systematic error of the pre-beam calibration of these BPMs, and then corrected this error for all other BPMs (having manually adjustable movers) as 1st step of the beam based calibration. The 2nd step – a beam based calibration using an optics model that itself is calibrated against screen monitors, wire scanners and CBPM8 etc. – is still to be performed, while the present uncertainty of the position scaling factors is expected to be <10% and thus sufficient for the ongoing commissioning of the SwissFEL accelerator and experiments.

Nonlinearity

Figure 6 and Figure 7 show the nonlinearity of a CBPM16 and CBPM38, measured by mechanically moving the BPM pickups in BC1 / BC2 and recording the BPM position readings (for a larger number of shots, to suppress noise/jitter) as function of the mechanical position encoder readings of the bunch compressors. The vertical axis shows the deviation from a linear fit (i.e. from perfect linearity). The measurement was performed first with automatic range control (ARC) active, where the FPGA changes the attenuators in 1dB steps to keep ADC readings at 50-70% full scale, and then with ARC inactive (DSA attenuation constant during pickup position scan). With ARC off, the nonlinearity is determined by the active components of the RFFE input signal chain, with ARC on the nonlinearity is determined mainly by the accuracy of the DSA calibration performed in the lab, where the DSA have a different attenuation (and different calibration constant) for each point in the plot.

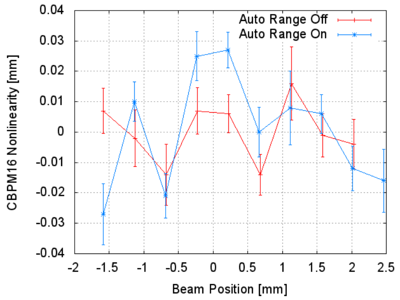

Figure 6: CBPM16 nonlinearity

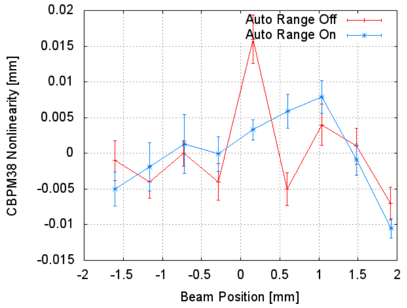

Figure 7: CBPM38 nonlinearity

Charge Resolution

Figure 8 and Figure 9 show the relative and absolute charge resolution of CBPM16 and CBPM8 BPMs, determined by correlating the readings of adjacent BPMs and assuming that there is negligible beam loss between the BPMs. Table 2 summarizes the result.

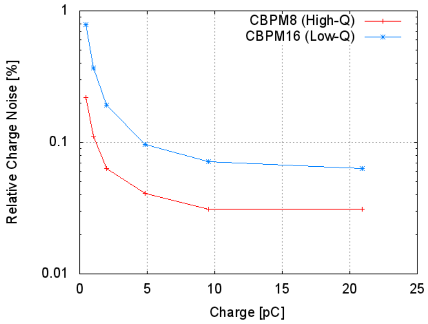

Figure 8: Relative single-bunch charge resolution, as a function of the bunch charge.

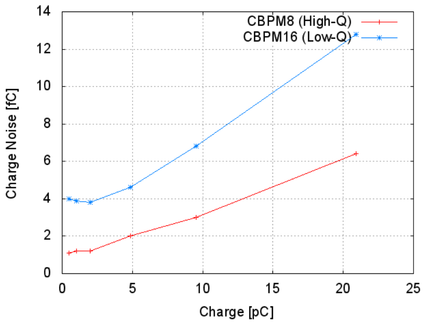

Figure 9: Absolute single-bunch charge resolution, as a function of the bunch charge.

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It should be noted that the BPM charge resolution is much better than the resolution of the dedicated charge monitors (ICTs and Faraday cups) of SwissFEL. Therefore the dedicated monitors are primarily used to calibrate the BPMs as well as for safety purposes (e.g. machine protection system), while the BPMs provide excellent resolution for the measurement of relative charge variations. It should be noted that the resolution was measured with constant DSA settings. The calibration error of the DSAs is presently not as good as the charge resolution, but could be improved to or beyond the charge resolution using beam-based inter-BPM correlation rather than a lab signal source for calibration.

Table 2: Measured SwissFEL BPM Charge Noise

	CBPM38 CBPM16	**CBPM8**
Relative Charge Resolution	< 0.07%	< 0.04%
Absolute Charge Resolution	< 5 fC	< 1.5 fC
Charge Range	0-400pC	

It should also be noted that all RFFEs have fixed additional attenuators in their charge channel (that are not needed in the position channel), to avoid that the RFFE is destroyed at very high bunch charge, where the SwissFEL RFFEs are guaranteed to survive continuous operation at 800pC beam (4x the nominal upper charge limit). If this upper "destruction" charge limit was reduced (e.g. by using an electron gun that cannot generate such high bunch charges), the charge resolution at very low bunch charge could still be improved significantly by removing the above mentioned fixed attenuators.

Position Resolution

Figure 10 shows the position resolution at smaller beam offsets as a function of the bunch charge, Figure 11 the product of resolution and charge that converges to a constant value towards very low bunch charges. Table 3 summarizes the results.

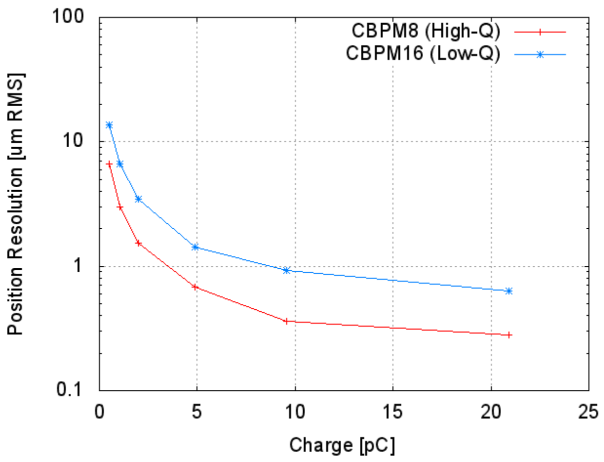

Figure 10: Absolute single-bunch position resolution as a function of the bunch charge.

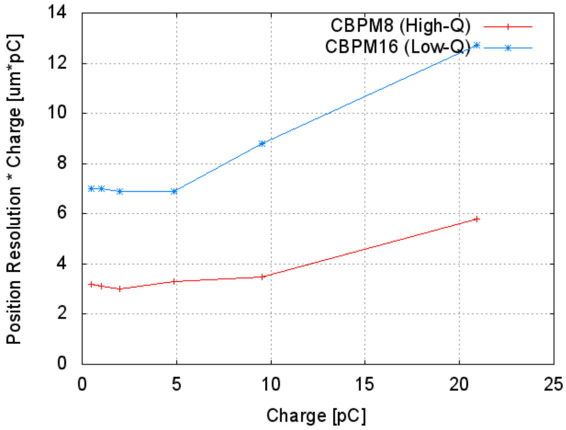

Figure 11: Product of single-bunch position resolution and charge, as a function of the bunch charge.

The resolution was determined by correlating the readings of three adjacent CBPMs of same type with similar beam offsets, where automatic range control was disabled. The method could not be applied to CBPM38 since there are no three adjacent pickups of this type in SwissFEL. However, CBPM38 and CBPM16 RF parameters are very similar, thus their resolution should be comparable (but is still to be measured with alternative methods).

Table 3: Measured Position RMS Noise

	CBPM16	**CBPM8**
Position Noise @ 10-200pC	< 1 µm	< 0.5 µm
Position Noise @ 1pC	< 8 µm	< 5 µm

SUMMARY AND CONCLUSION

The SwissFEL cavity BPM has been successfully put into operation. The measured position and charge resolution over the nominal charge range of 10-200pC exceeds the requirements (i.e. <0.1% for charge, <1µm for CBPM8, < 3µm for CBPM16, < 10 µm for CBPM38) and enables the future operation of SwissFEL at lower bunch charge. Already now, SwissFEL was operated at bunch charges down to 120fC during accelerator R&D shifts e.g. to generate ultra small beams, where the BPMs were still operational and provided usable orbit readings. While the basic commissioning of the BPM system is finished, work on beam-based calibration and improvement of the system is still in progress.

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