STATUS OF THE SwissFEL BPM SYSTEM

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Abstract

SwissFEL is a 5.8GeV free electron laser facility presently under construction at PSI. The electron beam position will be measured by three types of cavity beam position monitors (CBPMs). For the injector, linac and beam transfer lines, low-Q 3.3GHz cavity BPMs with 38mm and 16mm aperture (CBPM38 and CBPM16) will be used to measure the position and charge of two bunches with 28ns spacing individually. A fast kicker system distributes each bunch to a different undulator line, where 4.9GHz high-Q cavity BPMs with 8mm aperture (CBPM8) are used in the undulator intersections. The production of the CBPM38 pickups is finished, while the CBPM16 production is in progress. For CBPM8, a prototype pickup has been successfully tested, and a 2nd pre-series prototype with reduced dark-current sensitivity is currently in production. The development of the common 3.3GHz CBPM electronics for CBPM38 and CBPM16 is finished, while the CBPM8 electronics is currently in the prototyping phase. This paper gives an overview of the present pickup, electronics, firmware and software design and production status, including test results and methods to control and maintain the quality during series production.

INTRODUCTION

Table 1 lists the quantities and requirements for the SwissFEL BPMs [1]. CBPM38 pickups [2] are only installed at a few locations where a larger aperture is needed, e.g. at the beam distribution kicker, in beam dumps, or bunch compressor arms. The CBPM16 pickups [2] are used in most parts of the accelerator, except for the undulator intersections where the high-Q CBPM8 pickups [3] will provide higher (sub-micron) resolution and drift as required for the alignment and control of the electron-photon beam overlap in the undulators.

Table 1: SwissFEL BPM Quantities and Requirements

	CBPM38	CBPM16	CBPM8
Quantity*	7	114	51
Usage	Linac, Transfer Lines		Undulat.
Aperture	38mm	16m	8mm
Position Range	±10mm	±5mm	±1mm
Position Noise	<10µm*	<5µm*	<1µm**
Pos. Drift/Week	<10µm	<5µm	<1µm
Charge Noise	<0.1%***		
Charge Range	10-200pC		
#Bunches/Train	1-3		1
Bunch Spacing	28ns		10ms

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

Beam Energy Measurement

The CBPM16 and CBPM38 are also used at dispersive locations for beam energy measurement, e.g. in the arms of the bunch compressors between 1st and 2nd (as well as 3rd and 4th) dipole, or downstream of beam dump dipoles. For an expected position resolution of <1µm, the corresponding energy resolution is typically <2E-5.

Bunch Charge and Beam Loss Measurement

Like in the SwissFEL injector test facility (SITF), high-resolution charge measurements in SwissFEL will mainly rely on CBPMs since they provide higher resolution than dedicated charge monitors (ICTs, wall current monitors, etc.). CBPM16 prototypes achieved <0.07% relative resolution at high charge and <8fC absolute resolution at very low charge [1]. Since the pre-calibration of the CBPMs in the lab only provides ~10% scaling factor error for the charge, the CBPMs will be cross-calibrated with beam against dedicated charge monitors to achieve better absolute accuracy of ~1%.

BPM PICKUP DESIGN

All SwissFEL BPMs are cavity BPMs with two resonators. The so-called reference resonator has one (CBPM16, CBPM8) or two (CBPM38) standard couplers to measure the charge using the TM_{010} mode, while the position resonator has four couplers, using TM_{010} mode-suppressing waveguides to obtain the product of position and charge via the TM_{110} mode. By using the same working mode frequency for both resonators, undesired frequency-dependent drifts of the symmetrically designed BPM electronics are minimized. Both resonators also have the same loaded quality factor Q_L to obtain symmetric waveforms for minimal arrival time dependency of the CBPM electronics.

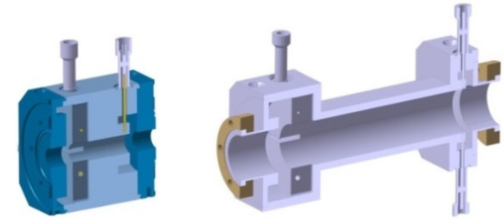

Figure 1: SwissFEL CBPM16 pickup (left) and CBPM38 pickup (right).

The CBPM16 and CBPM38 pickups are based on a SACLA design [4] that was also adopted for the E-XFEL [5][6]. For SwissFEL we did systematic simulation scans of all relevant pickup dimensions in order to achieve high resolution at low charge, and we also optimized the

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design and production for lowest costs while maintaining high quality. The CBPM16 and CBPM38 pickups are made of stainless steel (like SCACLA and E-XFEL pickups), while the CBPM8 has a new high-Q design consisting of a massive copper core brazed into an outer hull of stainless steel.

Table 2: CBPM Frequencies and Quality Factors

	CBPM38	CBPM16	CPBM8
Frequency	3.2844GHz		4.9266GHz
Q_L	40	40	1000

Choice of BPM Frequency and Quality Factor

The comparatively low bunch charge of SwissFEL motivates a high working mode frequency, since the theoretical resolution limit of CBPMs (neglecting cable losses and reflections) improves with higher frequencies. On the other hand, we wanted to simplify the electronics design, and keep phase drift effects (that increase with frequency) and cables losses reasonably low, where the BPM electronics will be completely installed outside the SwissFEL tunnel, with typical cable lengths in the order of 15-25m, suggesting a frequency below 6GHz. Moreover, the CBPM frequencies should not be too close to the frequencies of S-band and C-band structures to minimize possible interference noise. Finally, the working mode frequency of the pickups should stay well below the beam-pipe cut-off (i.e. <4GHz for CBPM38), and we wanted to use the same electronics for CBPM16 and CBPM38, while maximizing synergies with the E-XFEL cavity BPM electronics working at 3.3GHz. As a result, we chose 3.2844GHz for CBPM16 and CBPM38, and 4.9266GHz for CBPM8. Choosing e.g. 6.5GHz for the CBPM8 working mode frequency would not have led to a significant resolution improvement (while increasing drift effects and design effort), since the theoretical low-charge resolution improvement (relative to 4.9622GHz) is practically eliminated by increased cable losses and reflections.

For the CBPM38 and CBPM16, the chosen Q_L value of ~40 is low enough to simplify the digital bunch-to-bunch crosstalk suppression (the pickup signal of the 1st bunch has decayed to ~0.07% when the 2nd bunch arrives), but still large enough to allow easy sampling of the ~20ns long RFFE output pulse (that is not much longer than the pickup pulse). For the CBPM8, we decided to go from stainless steel to a copper resonator, which allowed to increase the Q_L from ~300 [1] to ~1000 without having significant resistive losses that were already ~15% for the stainless steel version, thus not compromising the resolution at very low charge. The higher Q_L simplifies the electronics design that uses mixing to an IF rather than mixing to baseband like for CBPM16 and CBPM38, and the ratio of range to resolution is also increased.

Dark Current Considerations

Table 2 shows the frequencies of the SwissFEL S-band and C-band accelerating structures and BPMs, as well as the multiplication factors for the 142.8MHz SwissFEL machine reference clock that are needed to obtain these frequencies. Since the smallest common multiple of S-band and C-band RF period is 7ns (i.e. the reference clock period), only every 7ns a dark current bunch manages to reach the undulators, while all other dark current bunches (bunched with the S-band RF gun frequency) are accelerated to the wrong energy and thus get lost in collimators upstream of the undulators. In order to avoid that the dark current excites the undulator CBPM8 pickups, we decided to increase the pickup frequency from 34 to 34.5 times the reference clock, such that the RF signals from adjacent dark current bunches interfere destructively in the CBPM8 pickups. For the less critical low-Q CBPM16 and CBPM38 pickups, we use an integer multiple of the reference clock as working mode frequency.

Table 3: SwissFEL RF Frequencies and Multiplication factors for the 142.8MHz Machine Reference Clock

System	Frequency	Ref Clock Multiplier
S-Band Injector	2.9988 GHz	21
C-Band Linac	5.712 GHz	40
CBPM16/38	3.2844 GHz	23
CBPM8	4.9266 GHz	34.5

BPM PICKUP PRODUCTION

RF Feedthroughs

For the SITF stripline BPMs, we designed RF feedthroughs in collaboration with a Swiss company (BC-Tech AG, http://www.bctech.ch) that produces them for us, for a fraction of the price of similar commercially available multi-GHz RF feedthroughs that we had purchased so far. The quality control of the feedthroughs at the company includes measurements of all mechanical dimensions, leak tests and electrical tests for every feedthrough. In addition, we did S-parameter measurements of all feedthroughs (see Figure 2), and high-temperature cycling test of samples with leak tests at high and low temperature at PSI. Figure 3 shows histograms of the S11 parameter measurements for the 1300 feedthroughs we have produced so far, excluding a smaller pre-series where we tuned and optimized the design and production process.

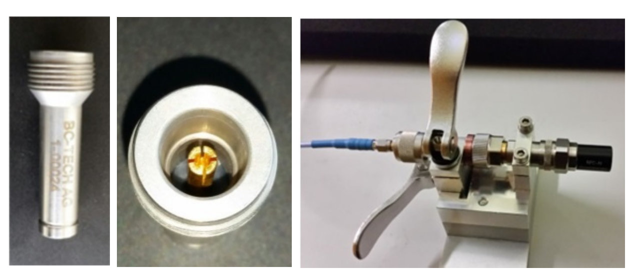

Figure 2: SwissFEL RF feedthrough (left, middle) with test adapter (right) that uses a standard APCN-7 adapter and 50Ω broadband load.

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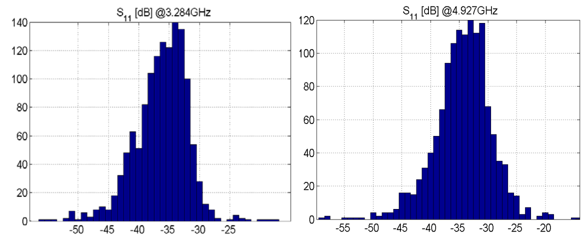

Figure 3: Histograms of measured S11 of the 1300 SwissFEL CBPM RF feedthroughs, for 3.2844 GHz (left) and 4.9266 GHz (right).

In order to keep the influence of the feedthroughs on the pickup RF parameters reasonably low, we defined a minimum requirement for S11 of <-25dB, aiming at typical values of <-30dB. As shown in the figures, this goal was reached for nearly all feedthroughs. Due to the low production costs, we produced more feedthroughs than we needed, thus allowing to sort out a smaller number with suboptimal performance.

Pickup Production RF Measurements

The body of the CBPM16 and CBPM38 pickups consists of three parts (see Figure 1 for CBPM16, parts colored differently) that are brazed together before the RF feedthroughs are welded to the body. The body parts are machined by an external company and then brazed and welded at PSI. The mechanical tolerances of the pickups were defined such that they reach the desired RF parameters while keeping the production reasonably simple and cost efficient. In addition to checks of all relevant mechanical dimensions of the body parts by the company, we also measured the pickup frequencies and Q_L before and after brazing. Before brazing, a special holder pressed the body parts and feedthroughs together such that they had sufficient and reproducible contact.

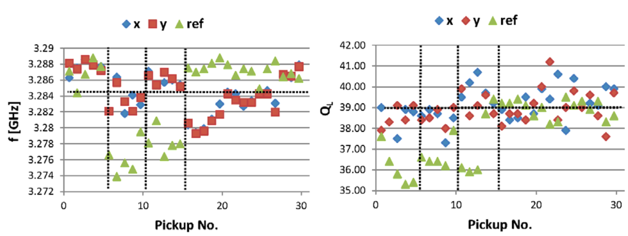

Figure 4: Frequency (left) and Q_L (right) of brazed CBPM16 pickups. Pickups no. 1-15 are a pre-series from 3 companies, no. 16-30 are the first batch of the SwissFEL series production.

Figure 4 shows the measured frequencies of the 15 pre-series CBPM16 pickups and the first batch of 15 series pickups, produced by the company that also made pre-series pickups no. 11-15. For the series, we empirically changed the reference cavity dimensions, intending to correct a small systematic deviation of the reference cavity frequency and Q_L in the pre-series. While we initially aimed at Q_L=40, we re-defined the nominal value to 39 for the series, since our main goal is to get the same Q_L (and frequency) for position and reference cavity, while the absolute value is less critical.

Table 4: Measured average position cavity (X,Y) and reference cavity (R) frequency and Q_L of 30 CBPM16 pickups before and after brazing/welding.

CBPM16	Before	After	Average
	Brazing/Welding		Difference
f_X [MHz]	3282.6	3284.6	2.0
f_Y [MHz]	3282.1	3284.5	2.3
f_R [MHz]	3282.5	3283.8	1.3
$Q_{L,X}$	39.06	39.11	0.05
$Q_{L,Y}$	39.03	38.92	-0.12
$Q_{L,R}$	36.42	37.80	1.39

Table 4 shows that the brazing led to an average increase of only 2.0MHz and 2.3MHz for the position cavity, and 1.3MHz for the reference cavity. We empirically optimized the frequency and Q_L to be close to the nominal value after brazing, and used the measured shifts to predict these values from the pre-brazing measurements. Figure 5 shows the difference of the frequency and Q_L of reference and position cavity (using the average of horizontal plane X and vertical plane Y for the position cavity). The values were measured before and after brazing/welding of the feedthrough parts. Especially for no. 11-30 (produced by the same company), the difference between pre- and post-brazing/welding measurement is rather small.

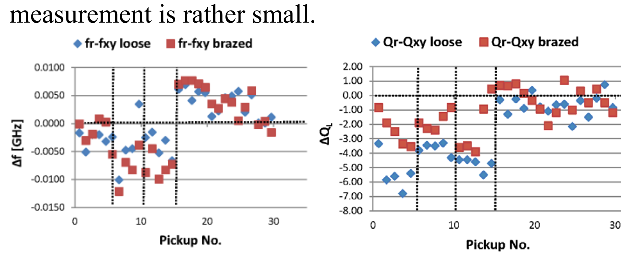

Figure 5: Difference of CBPM16 reference and position cavity frequency (left) and Q_L (right) before and after brazing/welding of the pickup parts.

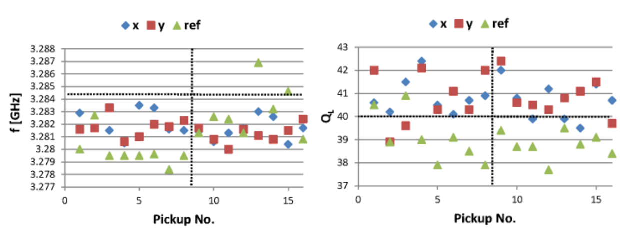

Figure 6: Frequency (left) and Q_L (right) of CBPM38 pickups.

Table 5: Average position cavity (X,Y) and reference cavity (R) frequency and Q_L of 16 CBPM38 pickups before and after brazing/welding

CBPM38	Before	After	Average
	Brazing/Welding		Difference
f_X [MHz]	3280.2	3281.8	1.7
f_Y [MHz]	3280.3	3281.5	1.2
f_R [MHz]	3280.0	3281.4	1.4
$Q_{L,X}$	42.9	40.8	-2.1
$Q_{L,Y}$	42.3	40.8	-1.5
$Q_{L,R}$	37.7	39	1.3

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Figure 6, Table 5 and Figure 7 show the respective RF parameter measurement results for the 16 CBPM38 pickups. Pickup no. 1-8 was a pre-series produced for KIT/FLUTE [7], no. 9-16 for SwissFEL.

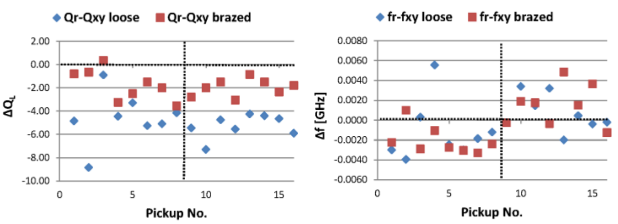

Figure 7: Difference of CBPM38 reference and position cavity frequency (left) and Q_L (right) before and after brazing/welding of the pickup parts.

Mechanical Supports

For cost reasons, all CBPM8 pickups and most CBPM16 pickups have mechanical supports where the position and angle of the pickup can only be adjusted manually via shimming plates with ~10µm position and 100µrad angle uncertainty for relative adjustments.

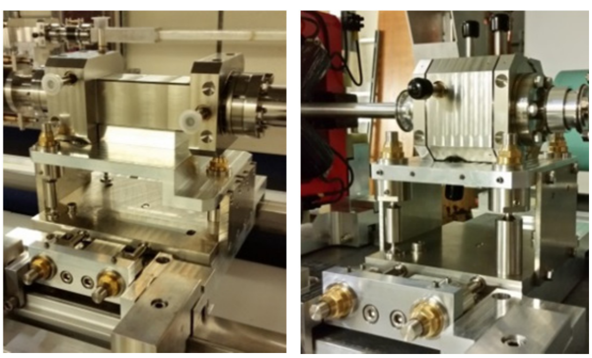

Figure 8: CBPM38 (left) and CBPM16 pickup (right) with manually adjustable supports.

Some CBPM16 where the performance (affected by angle misalignment) is critical and all CBPM38 have supports that are manually adjustable via differential screws with <2µm position and <20um (CBPM16) or <8µm (CBPM38) angle uncertainty. As already discussed in [8], this is sufficient to achieve the desired performance. In addition, the CBPM8 and their adjacent quadrupoles can be moved with a common motorized 2D mover system.

The SwissFEL building is now mainly finished, but not yet clean enough to install girders and diagnostics components in the accelerator tunnel. In order to reduce the installation time, BPMs and other components are currently pre-installed in other PSI buildings (where the photos in Figure 8 were taken) on their girders and then aligned relative to the girder. Then the complete girder with its components will be moved into the SwissFEL tunnel when it is ready and aligned relative to the tunnel reference system. When moving the girder with sufficient care, this should result in an acceptable alignment of all components relative to the beam, with the possibility of laser tracker and/or beam based re-alignment where necessary.

BPM ELECTRONICS

The SwissFEL BPM system is a modular design, consisting of a customized crate (MBU = Modular BPM Unit), where 2-4 RF front-ends and a digital carrier FPGA board with two ADC mezzanines (6 channel 16bit 160MSPS each) can be inserted from the front side. At the rear side, there are additional slots for a modular redundant power supply supporting intelligent power and temperature management, interlock board, and communication board with SFP+ transceivers and other inputs for feedback, optical (multi-gigabit) or copper cable based timing system signals, and control system interface (supporting Ethernet, PCIe, or custom multi-gigabit fiber optic link protocols).

Figure 9: Modular BPM unit, with two cavity BPM RFFEs (top) and FPGA carrier board with two ADC mezzanines (bottom).

Integrated Timing System Interface

The MBU does not require a dedicated interface board to the (MicroResearch) timing system of SwissFEL (or E-XFEL that uses a different timing protocol). Instead, it decodes the digital multi-gigabit stream of the timing system directly in one of the FPGAs of the digitizer board in the MBU using firmware developed at PSI.

CBPM16/CBPM38 Electronics

As already described in ref [9], CBPM16 and CBPM38 have a common BPM electronics based on an RFFE with IQ downconversion of the pickup signals to baseband.

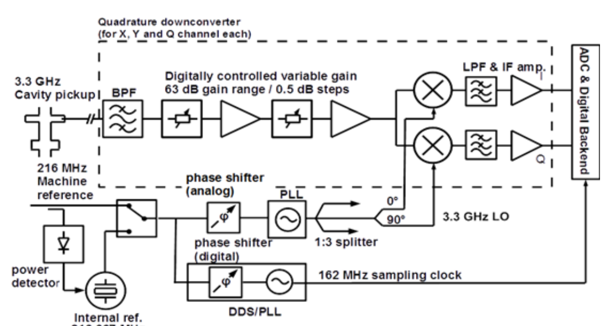

Figure 10: Simplified schematic of CBPM16/CBPM38 CBPM RFFE electronics, showing only one of its three input channels (one reference and two position signal channels).

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The differential RFFE output signal pulses of ~20ns length are sampled at the top with differential ADCs (employing baseline subtraction) and then processed by the FPGA carrier board to obtain position and charge, already in physical units as required for fast beam-based feedbacks. The FPGA board also controls various parameters of the fully programmable RFFE, performing ADC and LO clock phase feedbacks to keep the ADC clock phase and IQ phase constant, thus making sure the RFFE output pulses are always sampled at the top.

CBPM8 Electronics

In contrast to the CBPM16/38 electronics, the CBPM8 RFFE (shown in Figure 11) has only one mixer for each of the three pickup signals, and converts the signals to an IF frequency of 133MHz rather than to baseband.

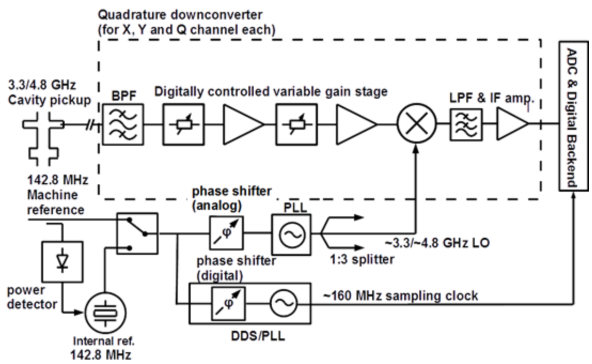

Figure 11: Simplified schematics of CBPM8 RFFE electronics, showing only one of its three input channels.

The electronics thus needs only three ADC channels per RFFE, and can use the same ADC board as the low-Q CBPMs. With 160MSPS sampling rate, the 16-bit ADCs convert the IF to a 27MHz signal that is digitally downconverted by the FPGA board to obtain position and charge via Cartesian-to-polar conversion and suitable filter and detector algorithms. Figure 12 shows a conservative estimate for the CBPM8 position resolution as a function of charge, assuming that a comparatively simple algorithm for the position calculation is used (based on matched filters and top sampling). For the maximum bunch charge of 200pC, <100nm resolution at ±200µm dynamic range is feasible, while the resolution at 10pC is still expected to be <1µm (for ±1mm range).

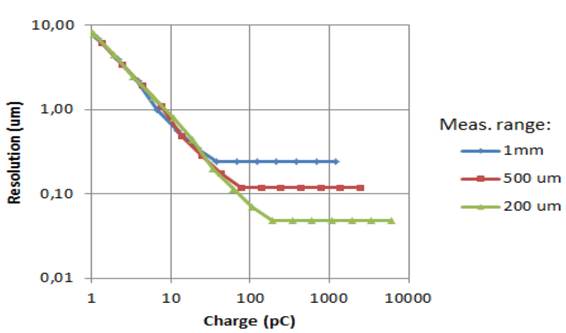

Figure 12: Estimated position resolution vs. bunch charge of the CBPM8 system for different measurement ranges.

While the CBPM16/38 electronics has already been tested with beam [1], the first CBPM8 RFFE is presently in production, with prototype tests at the SLS linac scheduled for end 2015.

SUMMARY AND CONCLUSION

The SwissFEL CBPM pickup production is in progress. The very cost-efficient RF feedthroughs and pickups produced so far have rather low RF parameter variations, ensured by constant quality control and monitoring during the production. By doing the most critical brazing and welding process in house, we so far managed to avoid any quality problems. For the CBPM electronics, we will soon start a pre-series production for the SwissFEL injector to be commissioned with beam in 3/2016, followed by series production and commissioning of the complete SwissFEL linac and undulators with beam in Q4/2016.

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