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THE SwissFEL HIGH-Q UNDULATOR BPM SYSTEM

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Abstract

In 10/2016, PSI started the beam commissioning of Aramis, the hard X-ray undulator line of the SwissFEL free electron laser. The injector, linac and transfer line BPMs have 3.3 GHz low-Q cavity BPMs to support 2-bunch operation with 28ns bunch spacing. In contrast, Aramis as well as the future 2nd soft X-ray undulator line called "Athos" are equipped with 4.9 GHz high-Q cavity BPMs, since the undulator will only be operated with single bunches by means of a fast beam distribution kicker system. The undulator BPM system uses 4.9GHz double-resonator pickups having a nominal loaded-Q of 1000. The associated front-end electronics applies single-stage analog down conversion to a 135 MHz IF frequency, subsampling ADC and digital quadrature down conversion. A detailed description of the BPM pickup and front-end design and signal processing will be given. Laboratory test and calibration methods and results of pickups and electronics will be compared with first beam measurements.

INTRODUCTION

The SwissFEL Aramis beam-line BPM system uses three types of pickups: Low-Q (Q=40) at 3.3GHz having 16mm or 38mm aperture in the linac and transfer line sections, and high-Q (Q=1000) 4.9GHz with 8mm aperture in the undulator section. A detailed description of the pickup design is given in [1].

Bunch spacing is 28ns in linac and transfer sections. Hence, low-Q cavity BPMs (CBPMs) are used in order to minimize signal leakage from the first into the second bunch. In contrast, the undulator section operates only with single bunches at a maximum repetition rate of 100 Hz. A high-Q cavity pickup is adequate here and provides higher resolution.

FRONT-END ARCHITECTURE

The high-Q CBPM front-end uses a combined analog/digital two-stage frequency conversion scheme. Figure 1 shows the front-end block diagram. The BPM signal enters an RF chain consisting of a first variable attenuator, a first RF amplifier, a second variable attenuator, a second RF amplifier and a band-pass filter. The variable attenuators establish a gain range of 60dB. The band-pass filter is centered at the nominal pick-up signal frequency, which is 4926.6 MHz.

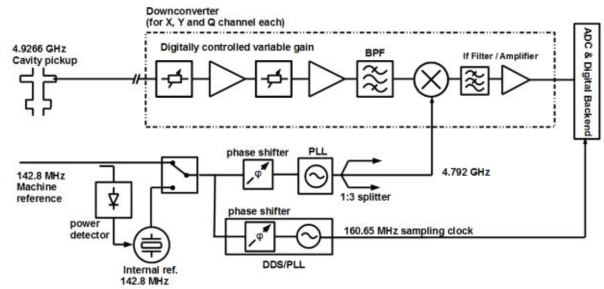

Figure 1: RFFE Block Diagram.

The band-pass filter rejects signal components and noise especially at the image frequencies, thereby improving resolution and reducing reading errors due to RF phase shifts. A local-oscillator signal at 4792 MHz is derived from a reference at 142.8 MHz. In the first (analog) down conversion stage the BPM signal is shifted to an IF frequency of 134 MHz. The IF section consist of an IF band-pass filter and an output amplifier. Both RF and IF stages are identical for position channels (x and y) and charge channel. A phase-adjustable 165.65 MHz clock used by the (separate) digitizer board is also generated on the RF front-end module. In nominal operation the reference frequency of 142.8 MHz is provided to the RFFE by the SwissFEL timing system. This signal is strictly bunch-synchronous. In case of reference failure an internal free-running reference oscillator switches in automatically. All frequencies generated are multiples of a common super-period frequency, which is 142.8MHz/72.

The second and final frequency conversion is done digitally on the separate FPGA board and will be described in the signal processing section.

Primary Design Guidelines

Development was guided by following major requirements:

- Nominal charge range: 10pC-200pC
- Useful readings below 1pC.
- No damage to the RFFE for charges up to 1nC, independent of gain setting.
- Single-shot resolution <1µm within nominal charge range
- Robust position and charge readings at varying RF phase and/or reference signal phase.

Front-End Module Construction

The front-end electronics is assembled on a 6-layer printed-circuit board. The size fits into a double width standard VME64x slot (Figure 2) of the modular BPM unit (MBU) crate. SMA connectors are provided at the

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front-panel for the machine reference signal, the ADC sampling clock, the RF inputs from the pick-up and differential IF output signals to the ADC. Electrical shielding and isolation between the front-end channels is provided by milled shields of aluminium on top and bottom side. The PCB is sandwiched between the screwed shields (Figure 3).

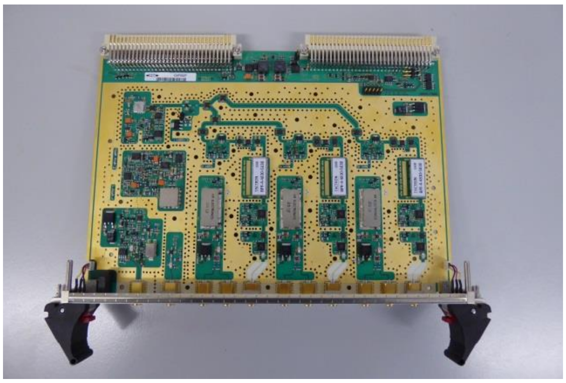

Figure 2: RFFE Electronics.

Figure 3: Front-End Module.

PICK-UP CONSTRUCTION

The BPM pickup uses a double resonator structure (Figure 4) and has been described in [1].

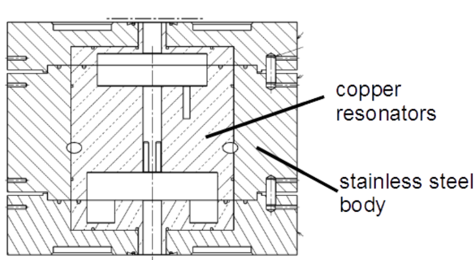

Figure 4: Cross-section of Undulator BPM Pickup.

The characteristic numbers of the pickup are given in Table 1.

Table 1: Cavity Parameters

Parameter	Value
Nominal Signal Center Frequency	4926.6 MHz
Reference Signal Sensitivity	58 V/nC
Position Signal Sensitivity	4.3 V/(nC·mm)
Loaded-Q	1000
Aperture	8 mm

The measured sensitivities of installed pickups vary less than +/-5% from their nominal values (Figure 5). These are 4.3 V/mm/nC for the position channels and 58 V/nC for the charge channel.

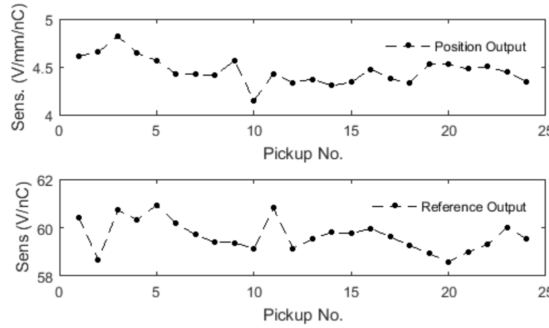

Figure 5: Sensitivity Parameter Variation.

The measured signal frequencies also have very little variation and are within ±4 MHz of the design value.

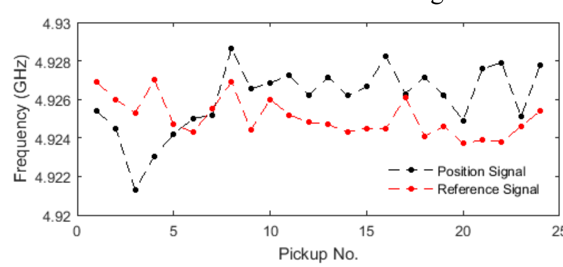

Figure 6: Signal Frequency Variation.

BPM INSTALLATION LAYOUT

Two 180°-hybrid signal combiners are attached to the pickup support (Figure 7). They combine the ports Y+/Y- and X+/X-, respectively, in order to gain signal amplitude. Several meters of ½'' corrugated RF cables take the pickup signals to the electronics rack located outside the tunnel in the technical gallery. The hybrid is connected to the pickup ports by short flexible RF cables.

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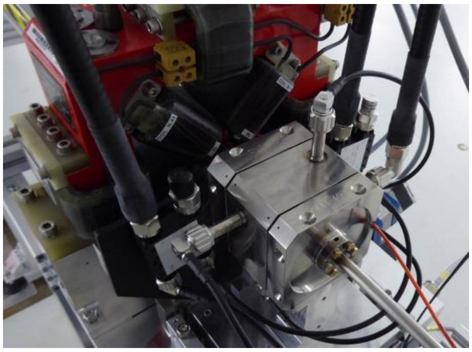

Figure 7: 8mm Undulator BPM Pickup at SwissFEL.

The reference resonator signal path contains a fixed attenuator mounted at the patch panel in the electronics rack. It reduces the potentially high reference pickup signal peak voltage to a safe level (Figure 8).

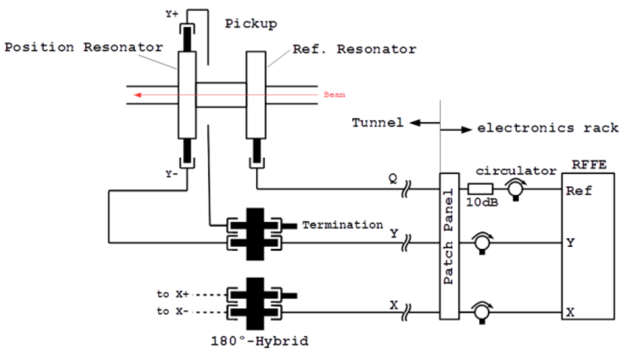

Figure 8: BPM Layout.

All RF signals run through isolators before entering the BPM electronics. The isolators reduce the impact of the gain-dependent input reflection factor on the BPM reading.

SIGNAL PROCESSING

The ADC signal samples are multiplied on the FPGA board of the BPM system by NCO sine and cosine waveforms (digital I-Q-downconversion, see Figure 9). This stage does the second frequency translation from IF to baseband. The sum signals are subsequently removed by a FIR low-pass filter.

The FIR output samples represent the in-phase and quadrature signal. Its amplitude and phase relationship are processed further into charge and position information.

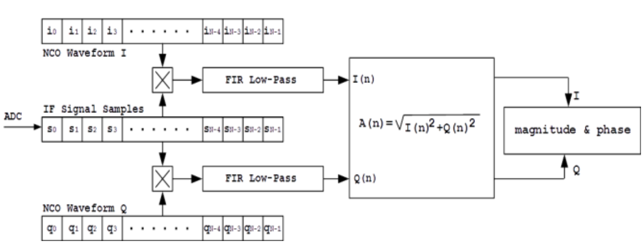

Figure 9: Sample Processing Scheme (One Channel).

Measured waveforms are shown in Figure 10.

The digital IF-signal (upper waveforms) is the analog IF (at 134 MHz) sampled at a rate of 161 Msps. These waveforms are multiplied by NCO generated in-phase and quadrature signals at 27 MHz. Figure 10 (bottom) shows the baseband signal of reference channel after FIR 10 MHz low-pass filtering.

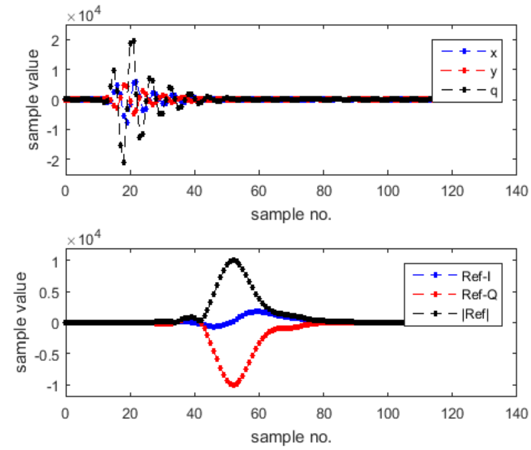

Figure 10: Digital IF Waveforms (top) and Reference Channel FIR Output (below).

Sampling phase adjustment is applied to keep one sample at the top of the magnitude waveform. This top-sample defines the sample number at which magnitude and signal phase is derived.

The pulse magnitude (that is then used to obtain beam positions and charge) is calculated from a quadratic interpolation taking into account the top sample and the two samples adjacent on both sides [2].

CALIBRATION

Due to component tolerances and other effects each BPM electronics unit is normally put through a calibration process in the laboratory prior to installation. The goal is to have charge and position reading independent from the setting of the RFFE gain. In addition charge and position readings are supposed to be sufficiently accurate for beam commissioning.

Procedure

The calibration is performed in two steps:

1. Calibration of the digital step attenuator stages due to non-ideal components characteristics.
2. Calibration of overall scale factors.

The laboratory calibration setup uses a signal generator with a 3x output splitter (Figure 11). In order to calibrate the digital step attenuator (DSA) of the RFFE, the signal generator provides a CW output signal at the nominal BPM cavity signal frequency. This results in a 27 MHZ CW waveform at the ADC output. The BPM system then records amplitude and phase of the generator output signal while scanning through all DSA settings automatically. Processing this information, a calibration table is generated and stored in local EEPROM on the RFFE board.

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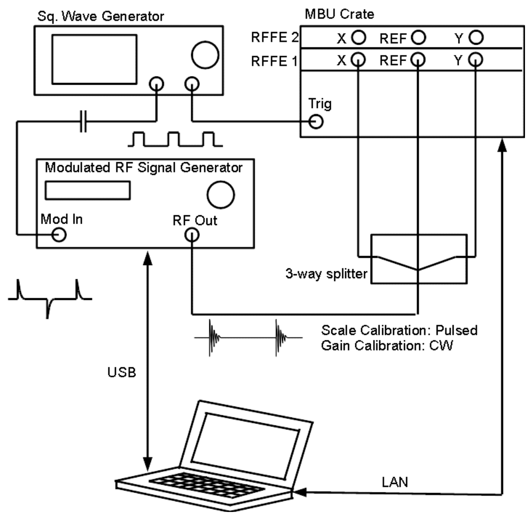

Figure 11: Calibration Set-Up.

This table corrects the measured signal amplitude based on the commanded gain and is further used in the calculation of position and charge.

Attenuator calibration using CW signals is sufficient. The use of artificial (decaying) pickup signals is not necessary due to the high Q of the pickups.

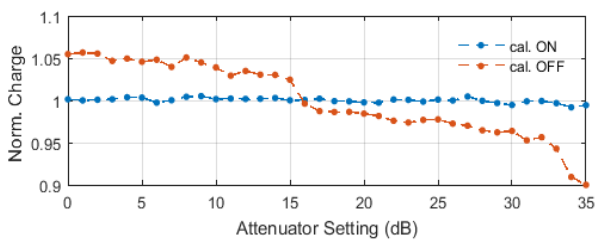

Figure 12: Charge Reading: Calibration on/off.

Figure 12 shows the charge reading while stepping channel attenuation from 0 dB to 35 dB at constant input signal amplitude. An uncalibrated attenuator leads to a reading error that may exceed 10%. Laboratory calibration reduces the error to below 1%. Further reduction requires beam-based procedures, because parameters of the installation (cable length, signal reflections in cable and feed-through, etc.) also affect the BPM calibration.

Scale factors essentially translate the results of the calculated digital baseband pulse amplitudes into the physical units of charge and position. Each BPM channel uses an internal scale factor (set by calibration routines in the lab and then left unchanged) and an external scale factor.

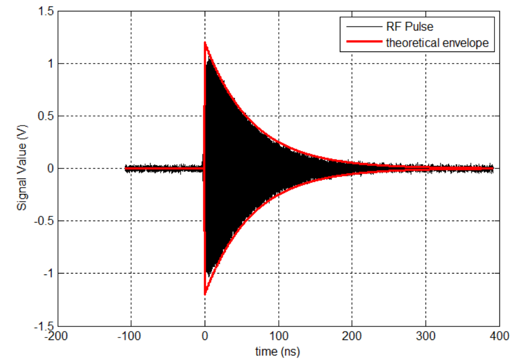

Figure 13: Calibration RF Pulse.

The internal scale factor calibration uses a modulated RF signal of defined amplitude and whose decay closely matches that of an actual cavity signal pulse having a loaded-Q of 1000. The external scale factor must be adapted individually at BPM commissioning by taking into account actual signal loss and pickup sensitivity for each BPM channel separately.

CONCLUSION AND OUTLOOK

The high-Q undulator BPM system installed at SwissFEL (Aramis beamline) has been described. Cavity pickup and measured parameters have been shown. The front-end electronics and its calibration have been described. Calibration procedure and verification measurements have been included. The high-Q BPM system has been successfully commissioned with beam, showing submicron resolution over the nominal bunch charge range [3]. User operation at SwissFEL will start in 2018, with pilot experiments already scheduled for late 2017.

ACKNOWLEDGEMENTS

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