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FIRST TEST WITH MICROTCA BASED CAVITY BPM ELECTRONICS FOR THE EUROPEAN XFEL AND FLASH

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Abstract

The European X-ray free-electron laser (E-XFEL) and the FLASH2020+ project for the free electron laser Hamburg (FLASH) at DESY in Hamburg, Germany foresee several machine upgrades in the years to come. At FLASH a whole undulator section in a shutdown starting in summer 2024 and finishing in autumn 2025 is going to be rebuild. Existing button beam position monitors installed in this section of the machine do not deliver sufficient signal strength for future required resolution specification and orbit feedback optimization for machine operation. The resolution limitations will be overcome by replacing the button-based beam position monitors with in-house developed cavity beam position monitors and compact microTCA based radio frequency receiver read-out electronics. The measurement system has been tested and evaluated in a test setup at FLASH.

INTRODUCTION

The two international user facilities European X-ray free-electron (E-XFEL) and the free-electron laser of Hamburg (FLASH) are operated by the Deutsches Elektronen-Synchrotron (DESY) in Hamburg, Germany. Both machines are based on the effect of self-amplified spontaneous emission (SASE) which generates ultra-short photon pulses by cascading several undulators. The photon pulses are based on accelerated electron-bunches which originate from a photo injector driven radio frequency (RF) electron gun. The electron bunches are accelerated in a pulsed superconducting linac at a repetition rate of up to 4.5 MHz. More specifications on the different machine parameters can be found here [1]. The high-resolution transversal beam position measurement of the electron beam along the machines is realized with cavity beam position monitors (CAVBPM). The E-XFEL is already equipped with well performing monitors including read-out electronics [2] from in-kind contribution partners. However, future planned upgrades of the machine [3] with additional CAVBPM will be based on in-house developed read-out electronics. Like the E-XFEL the FLASH facility will be upgraded with approximately 20 monitors within the FLASH2020+ project [4]. A CAVBPM electronics read-out system has been developed in the past few years and is already in operation [5]. These electronics have been modified and enhanced to meet the specifications of the E-XFEL and FLASH where the most demanding requirement is a single bunch resolution of better than 1 um in a charge range from 20 pC up to 1 nC. First tests with these CAVBPMs have been made with a test cavity BPM at FLASH to evaluate the adapted and extended read-out electronics. The charge has been varied over the specified range and the measurement results demonstrate to fulfill the specified resolution.

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CAVITY BEAM POSITION MONITORS AT FLASH AND XFEL

Cavity beam position monitors are composed of a mono-pole and a di-pole resonator from which the electron beam excited modes deliver RF signals from which the charge and the transversal position of the electron beam can be evaluated [6]. The monitors in use at the E-XFEL and in the design procedure for FLASH are also developed in-house [7] and have the characteristics listed in Table 1.

Table 1: Cavity Beam Position Monitor Characteristics E-XFEL and FLASH

Quality	Range
resonance frequency	3.3 GHz
beam pipe diameter	10 – 40.5 mm
mono-pole sensitivity	42.5 – 42.9 Vpk/nC
dipole sensitivity	2.46 – 2.87 Vpk/nC/mm
loaded quality factor	70

ANALOG SIGNAL DYNAMICS

The original developed CAVBPM monitor [8] and corresponding RF front-end electronics [5] have been designed to operate in a charge range from 500 fC up to 100 pC, while the specified charge range in the E-XFEL and at FLASH varies from 20 pC - 1 nC. Due to these different charge ranges and equivalent signal amplitudes modifications in the RF front-end were necessary. For this purpose a typical signal from a mono-pole resonator has been measured at a test cavity at FLASH. The signal is shown in Fig. 1.

Since the signals from the cavity are band-pass filtered in the first place in the RF front-end the signal strength from the band-pass filtered signal has been chosen to determine the necessary front-end dynamics. The derived quantities are summarized in Table 2.

Table 2: Estimation of Expected Signal Powers for the Charge Range From 20 pC–1 nC

Mode/States	Charge	voltage/Vpp	power/dBm
min. charge	20 pC	0.044	−23
max. charge	1 nC	22.25	31

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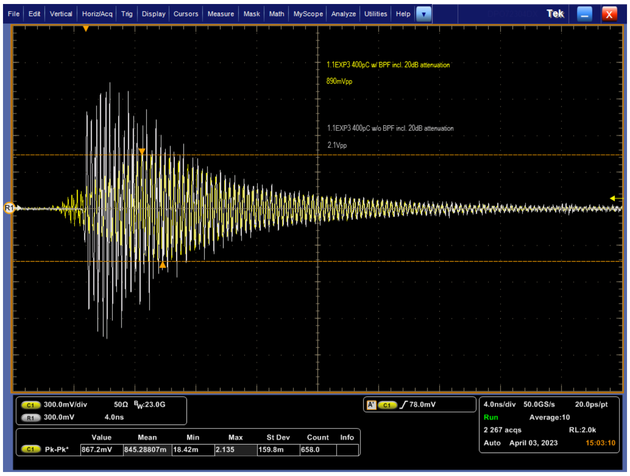

Figure 1: Analog signal from reference resonator and 20 dB additional attenuation measured at 400 pC. White trace: without band-pass filter. Yellow trace: with band-pass filter.

Therefore the mono-pole signal covers a dynamic range of approximately 60 dB with a headroom of 6 dB. A similar estimation for the signal level dynamics of the dipole signal has been made. The front-end receiver dipole channel can accept a minimum signal power of −76 dBm and a maximum of 37.75 dBm exceeding a dynamic range of 100 dB. Special care needs to be taken to avoid an operation of the front-end receiver components beyond the P1dB in amplifiers and demodulator. This is done empirically during commissioning of the electronics. For these first tests the RF front-end receiver introduced in [5] has been modified in the charge channel. The remaining component chain consists of a band-pass filter and a step-attenuator before the RF signal enters the demodulator.

MEASUREMENT SYSTEM SETUP

The measurement principle to estimate the resolution performance of the electronics is based on the idea to separate correlated beam-jitter and un-correlated electronics noise contributions in the measurement. This is done by splitting the signal from one cavity and measure the signal fluctuations in two identical electronics. To obtain a prediction of the position and charge measurement a singular value decomposition (SVD) of two independent measurement channels (either horizontal, vertical, or charge) is applied [9]. The remaining standard deviation of position and charge fluctuations reveals the un-correlated electronics noise from the two systems [1]. Figure 2 shows the connection sheet from the splitters to the modified RF front-end which is housed in a Micro TCA crate.

Data Acquisition

The signals received by the modified RF front-end receiver are digitized on a separate electronics card with six analog

[1] Excluding the losses in the splitter, which promises an improved resolution by at least a factor of $\sqrt{2}$.

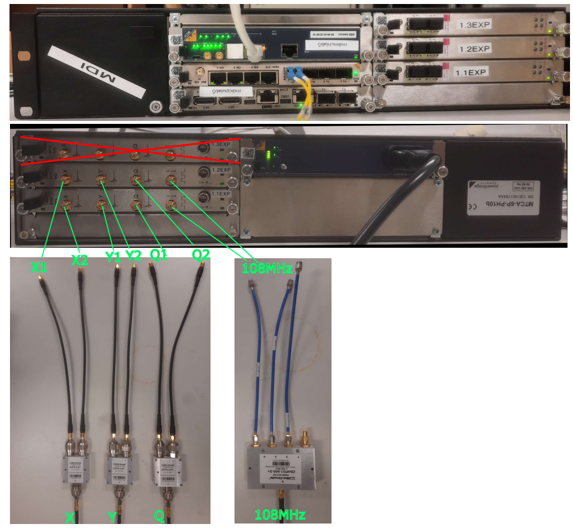

Figure 2: Micro TCA based read-out electronics including CPU, MCH, X2timer, and three digitizer cards. Three power splitters for x,y and q signals from the cavity and an additional splitter for the Master Oscillator reference frequency of 108 MHz.

to digital converters with a 16 bit resolution and a sample rate of 108 MHz. The digitized data is collected in a field programmable gate array (FPGA) and the sampled data is accessed by a hardware (HW) server process in which the final calculation of beam charge and position takes place. To synchronize the local oscillator (LO) phase and obtain phase stable measurements it is necessary to program the phase locked loop (PLL) on the RF front-end receiver from the server panel shown in Fig. 3.

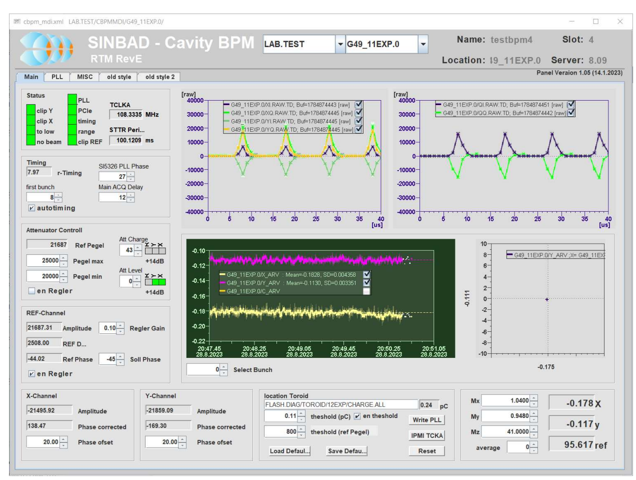

Figure 3: Hardware server with RF front-end interface, raw data read-out and calculated horizontal and vertical position and charge data.

Additional important features of the server are:

- data timing and phasing of intermediate (IF) signals
- a global gain control to adjust signal level depending on charge and x,y-offset

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- LO reference phase control to stabilize the reference cavity with respect to machine phase and optimize stability and reproducability
- phase offset which need to be adjusted once to find the correct quadrant and sign of di-pole signals phase change
- scaling factors for x, y, and q to adjust calculated values to reasonable physical quantities.

Calibration

The test cavity BPM is mounted on a mover stage with an internal accuracy of 1 µm which can be moved during electron beam operation. Finding the correct scaling factor has been done in an iterative manner by physical movement of the cavity with the help from the mover stage and then comparing the measured value from the electronics. After comparison the scaling factor has been corrected so the measured value matches the physical movement. This has been done over a measurement range of +/- 500 µm. The scaling of the charge values has been done by comparing the readings from a nearby charge measurement monitor and adjusted accordingly to deliver similar results.

MEASUREMENT RESULTS

A synchronous read-out of position and charge data for 220 subsequent bunches has been realized to enable the separation of correlated beam jitter and the un-correlated electronics noise. The result can be shown as a function of the predicted value for the measured charge and position data sets. During the measurement the minimum measured charge has been 19 pC and the maximum was around 307 pC. Figure 4 shows the measured charge versus the predicted charge at 19 pC and Fig. 5 shows the measured x-position versus the predicted x position at a charge of 91 pC.

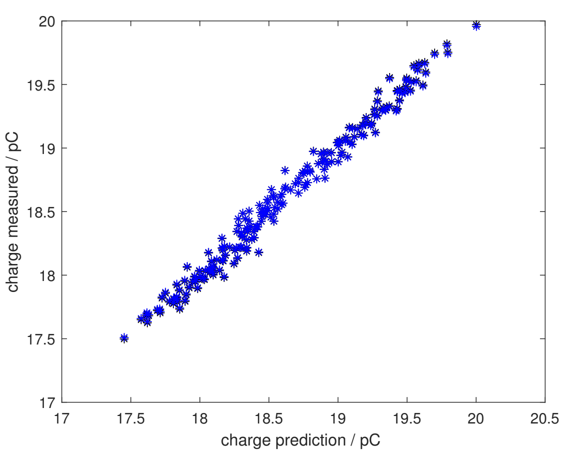

Figure 4: Correlated electronics noise from charge channel front-end receiver. The average charge is avg_q=18.78 pC and the standard deviation of the uncorrelated measurement noise is σ_q = 74 fC.

The following Table 3 shows additional charges where measurement data has been analyzed.

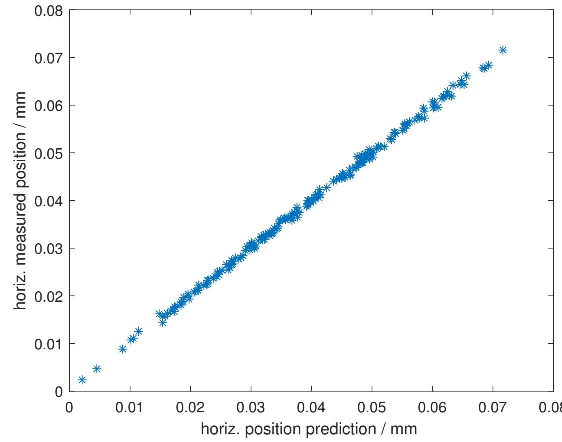

Figure 5: Measured x-position versus the predicted x position. The average charge here is σ_q = 91 pC and the standard deviation of the uncorrelated horizontal jitter is σ_x = 0.542 µm.

Table 3: Calculated resolutions based on measurements at FLASH at different charges. The calculation do not include the factor of $\sqrt{2}$ to compensate for the losses in the splitter.

Charge [pC]	σ_q **[fC]**	σ_x **[µm]**	σ_y **[µm]**
18.78	74	2.637	2.737
91	177	0.542	1.09
153	279	0.795	1.421
307	437	0.412	0.895

SUMMARY AND CONCLUSION

The measurements show that required electron beam position resolution of 1 µm could almost be met for a large charge range neglecting the fact of a reduced signal power of −3 dB in each RF front-end due to the power splitters in the measurement setup. The RF cables from tunnel to rack in this setup is about 50 m long. RF cables in existing cavity BPMs at E-XFEL and for future installations at FLASH2020+ will be more on the order of 30 m which will improve the signal to noise ratio to finally meet the specification goal of 1 µm also at the small charges of 20 pC.

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