FLASH UNDULATOR BPM COMMISSIONING AND BEAM CHARACTERIZATION RESULTS

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Abstract

Recently, the commissioning of FLASH2 has started, a new soft X-ray FEL undulator line at the DESY FLASH facility. In the FLASH2 undulator intersections, the beam positions are measured by 17 cavity beam position monitor (CBPM) pick-ups and electronics [1] developed for the European XFEL (E-XFEL). In addition four CBPMs are available at FLASH1 for test and development. The new CBPM system enables an unprecedented position and charge resolution at FLASH, thus allowing further analysis and optimization of the FLASH beam quality and overall accelerator performance. Results of first beam measurements as well as correlations with other FLASH diagnostics systems are reported.

INTRODUCTION

Beam position monitors (BPM) are an essential tool for the operation of a Free-electron laser (FEL). In the European X-FEL, cavity BPMs with sub-micron noise and drift are used for the alignment of the electron beam with the photon beam in the undulator area [2]; for a detailed description of a cavity BPM see [3, 4].

In addition to the undulator CBPMs with 10 mm aperture and 100 mm length, a second CBPM type with 40.5 mm aperture and 255 mm length will be installed in some locations in the warm beam transfer lines where the resolution of the standard button BPMs is not sufficient. A test area for the verification of the performance of both CBPM types has been installed at FLASH1 after the last undulator, see Fig. 1. The CBPM electronics, including its embedded FPGA firmware and software, is provided in an In-kind contribution from PSI, see Fig. 2. Both CBPM types have the same electronics because the BPM pickups have the same frequency of 3.3 GHz and similar loaded Q for their position and reference resonator.

In addition to FLASH1, a second undulator beamline FLASH2 [5] has been built to extend the capability of the FLASH soft X-ray FEL facility [6]. For the FLASH2 CBPMs, a pre-series for E-XFEL are used, with the BPM pickups provided by DESY and the electronics from PSI. In this report the results of CBPM measurements at FLASH1 and FLASH2 are reported, including comparisons with other monitors.

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Figure 1: CBPM test-stand at FLASH1 with three undulator CBPMs (right) and one 40.5 mm beam pipe diameter CBPM (left). The beam passes the pickups from right to left. Each CBPM can be moved in both transverse directions with remote movers.

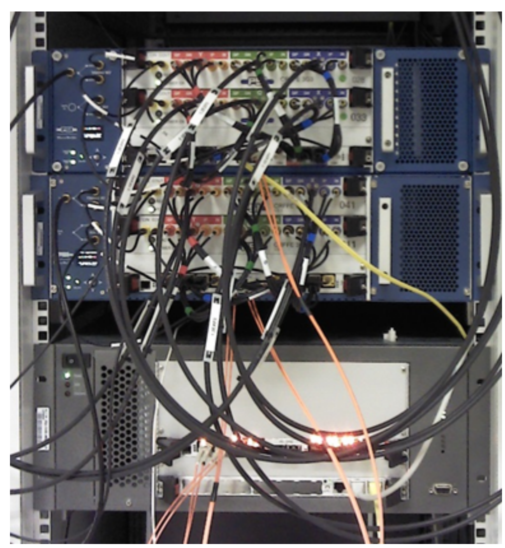

Figure 2: CBPM electronics provided by PSI for FLASH1 and FLASH2. For testing and verification purposes, the system was connected in parallel to the DOOCS based control system of FLASH, and also to EPICS based control system hardware provided by PSI for the commissioning of the systems.

CBPM AT FLASH1

The resulting position and charge values provided by the PSI electronics are transferred to the FLASH control system via an additional communication server. A rough calibra-

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tion was done for the charge and position readings using a nearby Toroid and remotely controlled transverse movers for each CBPM, see Fig. 1. To calibrate the position readings more exactly a beam jitter independent method from [3] is extended to the four CBPMs in the test area described in the following. Assume z_i are the installed positions of each CBPM i next to each other with only drift space in between where each CBPM can move by m_i, see Fig. 3. Each CBPM

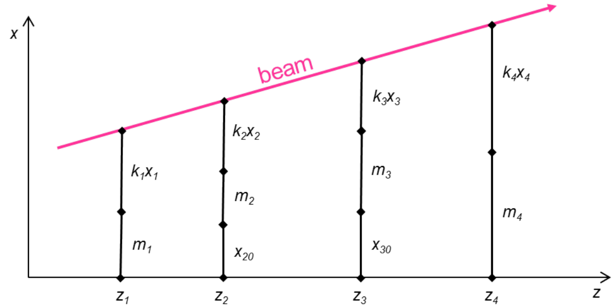

Figure 3: Sketch for the calculation of the calibration.

delivers a position x_i which has to be corrected by a constant k_i (the method is explained for horizontal plane but is used for the vertical plane y too). Both middle CBPMs are allowed to have a relative offset x_{20} and x_{30} with respect to a line between all four BPMs. This results in a condition to be fulfilled:

$$\frac{(k_2x_2 + m_2 + x_{20}) - (k_1 + m_1)}{z_2 - z_1 = z_{12}} = \frac{(k_4x_4 + m_4) - (k_3x_3 + m_3 + x_{30})}{z_4 - z_3 = z_{34}}.$$

Reordering the equation to

$$\frac{m_2 - m_1}{z_{12}} + \frac{m_3 - m_4}{z_{34}} = \frac{k_1x_1 - k_2x_2 - x_{20}}{z_{12}} + \frac{k_4x_4 - k_3x_3 - x_{30}}{z_{34}}$$

such that the right side can be written in vectors

$$= \begin{pmatrix} \frac{x_1}{z_{12}} & -\frac{x_2}{z_{12}} & -\frac{x_3}{z_{34}} & \frac{x_4}{z_{34}} & -\frac{1}{z_{12}} & -\frac{1}{z_{34}} \end{pmatrix} \begin{pmatrix} k_1 \\ k_2 \\ k_3 \\ k_4 \\ x_{20} \\ x_{30} \end{pmatrix}.$$

For several measurements the first vector becomes a matrix P and the vector with the mover positions a vector $\vec{M}$ such that the equation is rewritten to $\vec{M} = P\vec{k}$, where $\vec{k}$ contains the unknown calibration values. The solution is $\vec{k} = P^{-1}\vec{M}$. To solve the equation system at least 6 measurements at different mover positions m_i have to be performed.

This method was applied to the four CBPMs at the FLASH1 test area. Each CBPM was moved separately with about 200 μm step size, see Fig. 4. For each CBPM, 5 steps

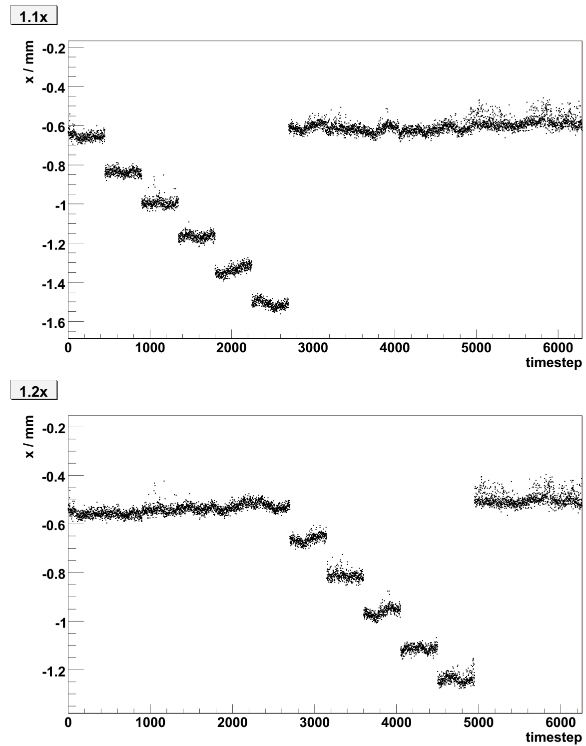

Figure 4: Position readings for different mover positions in x for first (1.1x) and second (1.2x) CBPM.

were used, with 450 position and charge measurements for each step. The histogram in Fig. 5 shows an example from the resulting calibration table that we obtained from the measurement. In this example, the approximate calibration

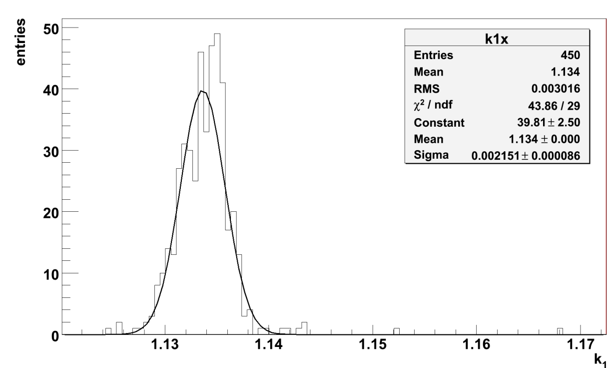

Figure 5: Histogram for different calculated correction values of first CBPM in horizontal direction with Gaussian fit.

obtained from the pre-beam measurements differs by ~13% from the more accurate beam-based calibration.

With the calibrated CBPM of the test-stand one can measure the beam positions and compare them with each other. The 3 BPM method is applied which is described in detail in [3]. Here two BPMs are used to predict the position at the third BPM. The difference from measured and predicted value results in a residual; one example of a residual

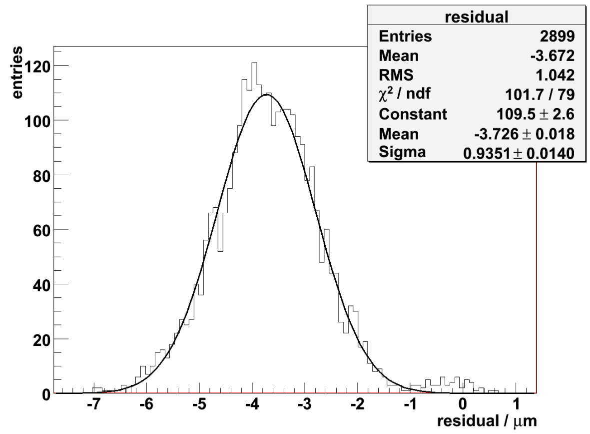

Figure 6: Residuals at a mean beam offset of 0.46 mm and charge 240 pC with Gaussian fit.

histogram is shown in Fig. 6. The Gaussian fit delivers a standard deviation which is used with a geometric factor (see [3]) to calculate the CBPM noise. The noise for both transverse planes are shown in Fig. 7 for different beam offsets at a charge of about 240 pC. The noise is increasing with the

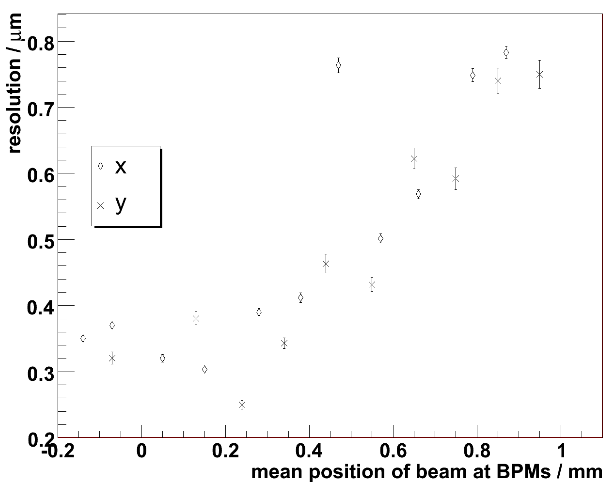

Figure 7: Resolutions of the undulator CBPMs at FLASH1 for different mean beam offsets in x and y for a charge of about 240 pC.

beam offset as expected, since the normalization of the position cavity to the reference cavity signal causes noise of the position that increases with larger beam offsets. For E-XFEL, the required single-bunch position noise for a stable beam with constant charge is below 1 μm for ±0.5 mm measurement range and 0.1 - 1 nC bunch charge. This requirement is already fulfilled by the E-XFEL pre-series electronics used in FLASH1 and FLASH2, where further improvements for the final system are expected by improved calibration and signal processing techniques. In addition one can compare the measured charge values of each CBPM and correlate them to calculate the charge resolution; for 240 pC charge, a resolution of 0.13 pC was obtained.

CBPM AT FLASH2

In FLASH2 17 CBPMs of an E-XFEL pre-series are installed between the undulators, see Fig. 8. In addition to

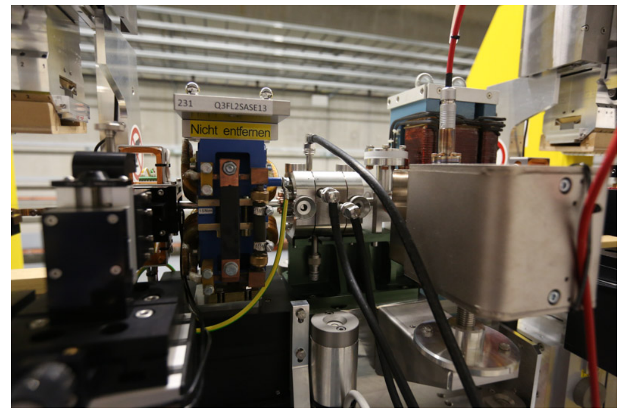

Figure 8: Undulator CBPM in an intersection of FLASH2.

supporting FLASH2 user operation, this gives the opportunity to get experience with the operation and beam-based calibration of a CBPM system in a working accelerator before E-XFEL is commissioned. The electronics for 4 CBPMs (provided by PSI) is shown in Fig. 9. Before first beam, the CBPMs have already been pre-calibrated, using e.g. measured RF properties of the pickups and cables, and signal generators for the electronics. Therefore, to get first beam position and charge readings, only the suitable trigger delay needed to be adjusted. The electronics also has a self-triggered mode using the reference cavity signal, but since the signal threshold may not always be reached during first commissioning (e.g. when the beam is lost somewhere), the external trigger was used.

Since the CBPMs are already integrated into the DOOCS control system (with a parallel EPICS system from PSI for test and verification), CBPM measurements could be compared with other FLASH diagnostics and subsystems.

For the absolute calibration of the CBPM charge measurement, the standard FLASH Toroid charge monitor was used. Thanks to a good pre-calibration, only a correction of 2.9% was necessary (except one CBPM with a correction of 21%, where maybe a measurement of the cable attenuation failed); this indicates that maybe the position calibration may have similar small corrections between pre- and beam calibration.

To get a first impression of the BPM system at FLASH2 the charge reading values are compared with Toroids. A mean charge value for each bunch is calculated such that the deviation due to a single monitor noise is negligible, except one monitor under test. This results in a difference between expected and measured charge for the monitor under test, see an example in Fig. 10. The standard deviation from the Gaussian fit shows the sum from systematical and statistical measurement errors, defined here as *sum error*. For all

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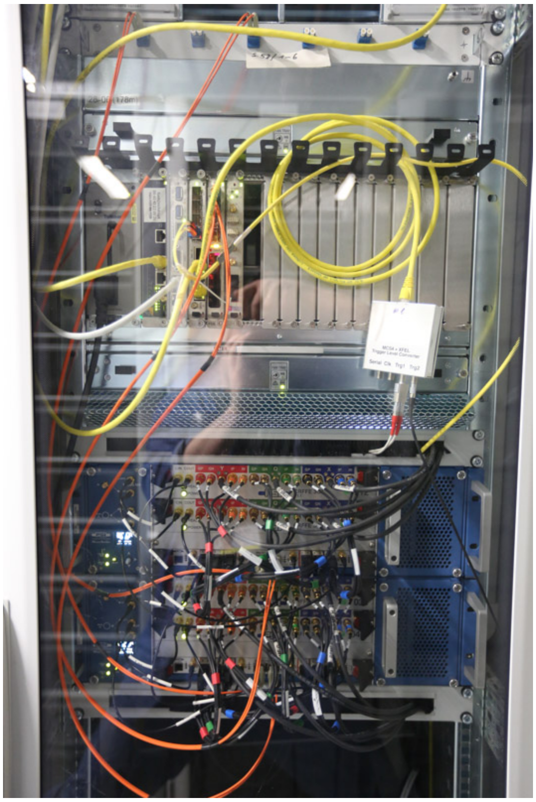

Figure 9: Undulator electronics for FLASH2 provided by PSI at the bottom part with 4 front-ends. Above is a μTCA crate with an FPGA/SFP board for the communication between PSI electronics and FLASH control system via fiber optic multi-gigabit links.

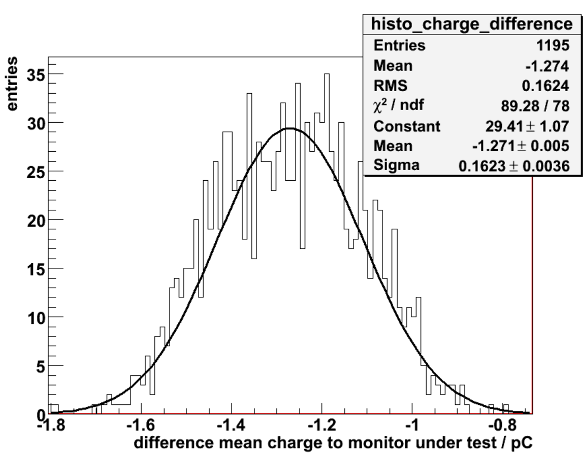

Figure 10: Difference between mean charge value to the monitor under test: here CBPM with the monitor number 19 with Gaussian fit at a charge of about 100 pC.

charge monitors these are shown in Fig. 11. All values above 0.6 pC are delivered by Toroids; therefore the CBPMs deliver better sum errors than standard charge monitors and are between 0.1 and 0.17 pC for a charge of 100 pC.

To obtain the position sum error (including statistical and systematical errors) two button BPMs after the accelera-

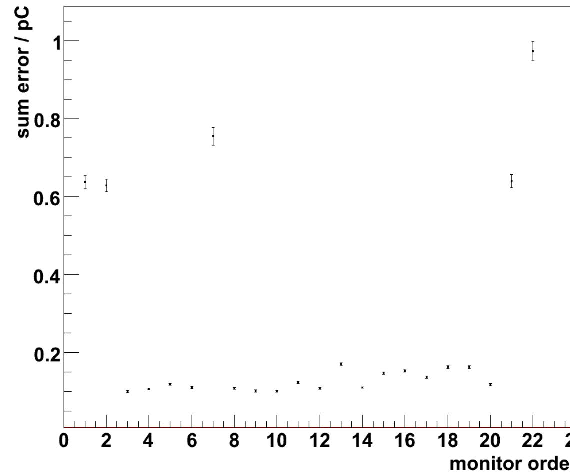

Figure 11: Sum of statistical and systematic errors of charge monitor correlation at FLASH2 at a charge of about 100 pC, with active automatic gain control of the CBPMs, ordered according beam direction. Values above 0.6 pC are from Toroids, values below from CBPMs.

tion modules and all CBPMs at FLASH2 are used. Here a correlation is calculated between each BPM and the BPM under test; the difference between expected and measured position value is obtained, for a reference of this method see [7]. An example of a difference histogram of one CBPM is shown in Fig. 12. All position sum errors of the BPMs

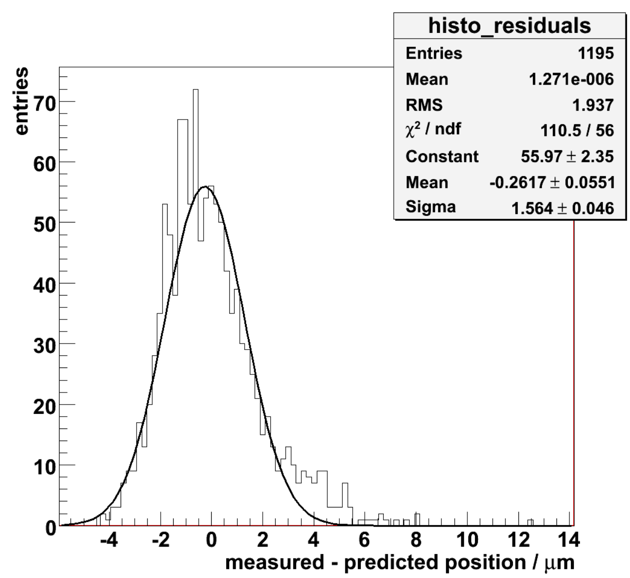

Figure 12: Difference between expected and measured position with Gaussian fit of a CBPM with monitor number 4 for position error calculation at the horizontal plane.

are shown in Fig. 13. Due to different beam positions, e.g. vertical sum error vs. mean beam position (see Fig. 14), the sum error is different at each CBPM, similar to the results shown in Fig. 7. As expected the sum error of the

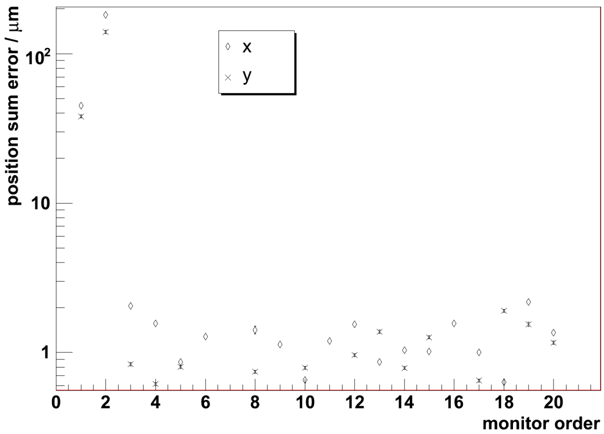

Figure 13: Sum error of BPM correlation at FLASH2 in both transverse planes for a charge of about 100 pC. The first two monitors are button BPMs, otherwise the order of CBPMs is similar to Fig. 11.

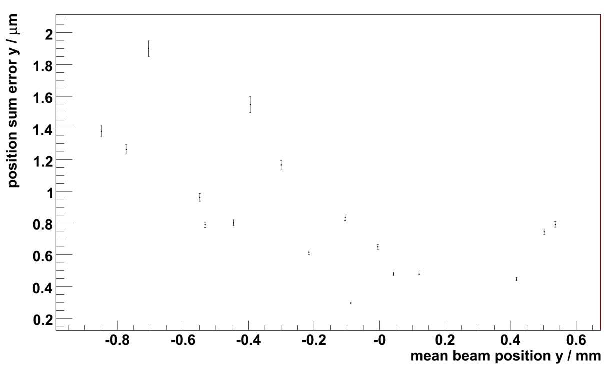

Figure 14: Sum error of CBPM correlation measurement at FLASH2 at the vertical plane with a charge of about 100 pC as a function of mean beam position.

correlation is much better for the CBPMs compared to the button BPMs. The sum error obtained for the CBPMs has several contributions. While the CBPM measurement in FLASH1 was done with constant attenuator settings (like later for the E-XFEL undulators), the CBPMs in FLASH2 were operated in a preliminary commissioning mode where a feedback loop permanently adapted the attenuators of the RFFE channels to the strongly varying charge and beam positions that may occur during first beam commissioning of an accelerator. Since the attenuators of the CBPMs were so far only approximately calibrated, the frequent changes of the attenuators caused systematic measurement errors of position and charge that usually dominate the sum error. In case of large beam position changes, the ADCs of the BPMs may saturate, which is indicated by the BPMs via a valid flag but not yet recorded by the control system, which also contributes to the measurement error. Finally, mechanical vibrations of the CBPM pickups or systematic errors of the measurement method itself (e.g. due to dispersive effects or X/Y rotation of pickups that has so far not been accounted for) can contribute to the overall error. A more detailed analysis of the individual contributions is in progress, where the goal is to minimize systematic contributions to the BPM measurement error via improved lab-based and beam-based calibration methods [8], leaving thermal RFFE noise and ADC resolution as dominating factors.

SUMMARY

The development of the CBPM system for the European XFEL is in an advanced state. An E-XFEL pre-series version of the CBPM pickups and electronics has been installed and tested in FLASH1 and FLASH2, and already fulfills the requirements for E-XFEL. Future activities will focus on improvement of lab and beam-based calibration techniques, as well as on improved automated range control and digital signal processing to further improve the CBPM system performance.

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