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TESTS OF A NEW BPM LONG TERM DRIFT STABILIZATION SCHEME BASED ON EXTERNAL CROSSBAR SWITCHING AT PETRA III

G. Kube, F. Schmidt-Föhre, K. Wittenburg, Deutsches Elektronen-Synchrotron DESY, Germany
A. Bardorfer, L. Bogataj, M. Cargnelutti, P. Leban, P. Paglovec, B. Repič, I-Tech, Solkan, Slovenia

Abstract

For the new PETRA IV project at DESY, about 800 high resolution BPMs will be installed with the readout electronics system based on MTCA.4 as technical platform. In order to fulfill the requested long–term drift requirement to be less than 1 micron over a period of six days (one week of user operation), due to the machine–specific geometry the BPM cable paths have to be stabilized in addition. To achieve this demand, the well proven concept of crossbar switching was extended such that the analogue switching part is separated from the read–out electronics and brought as close as possible to the BPM pickup. This contribution summarizes first proof–of–principle measurements which were performed at PETRA III using a modified Libera Brilliance+ with external switching matrix. These measurements indicate that the concept of external switching works well and that the performance of this modified test setup fulfills the specifications.

INTRODUCTION

The PETRA IV project at DESY aims to upgrade the present synchrotron radiation source PETRA III into an ultralow-emittance source which will be diffraction limited up to X-rays of about 10 keV [1]. Using a hybrid six bend achromatic (H6BA) lattice with a unit cell providing an emittance of 45 pm rad, the target emittance of about 20 pm rad will be recovered by a large number of damping wigglers distributed in the short straights of the octants not equipped with user beamlines [2]. This small PETRA beam emittance translates directly into much smaller beam sizes of 7 µm in both planes at the insertion device source points, thus imposing stringent requirements on the machine stability. In order to measure beam positions and control orbit stability to the requisite level of accuracy, a high resolution BPM system will be installed which consists of about 800 individual monitors with the readout electronics based on MTCA.4 as technical platform.

In Table 1 the BPM readout specifications are summarized. As demonstrated already in Refs. [3, 4], the listed requirements are achievable with the commercial Libera Brilliance+ (LB+) system [5]. However, in order to fulfill the requested long-term drift requirement for the case of PETRA IV, the specific machine geometry has to be taken into account. Originally, PETRA was built in 1976 as an e^-/e^+ collider for high–energy physics, later on acting as pre–accelerator for the hadron–electron ring accelerator HERA, then converted into the 3^{rd} generation synchrotron light source PETRA III which started operation in 2009 [6]. Due to the history as high–energy physics collider, the PETRA machine circumference of 2304 m is much larger compared to light sources built in the last two decades, and the machine infrastructure is distributed in the former experimental halls with the result of long cable lengths between monitor and readout electronics. Driven by considerable cost saving, the plan for PETRA IV is to reuse again the existing ring tunnel in the areas between the experimental halls as shown in Fig. 1. However, the tunnel cross section is too small for housing all required cables, i.e. it will not be possible to interconnect BPM pickups in the accelerator with their corresponding readout electronics in an experimental hall using cable paths inside the accelerator tunnel. As consequence, additional cable access shafts will be required to minimize the arising load inside the tunnel, and it is not guaranteed that cable routing will be in a perfectly stabilized temperature and humidity environment, thus affecting the BPM position readings [7, 8]. Therefore, in order to fulfill the requested long–term drift stability the BPM cable paths have to be stabilized in addition.

Table 1: Readout electronics specifications. The single bunch / turn resolution holds for 0.5 mA bunch current, the closed orbit one for 1 kHz bandwidth, the beam current dependency for a 60 dB range with centered beam, and the long term stability should be measured over 6 days and a temperature span of ±1 deg within a stabilized rack.

Requirement	Value
single bunch / single turn	< 10 µm
closed orbit resolution	< 100 nm (rms)
beam current dependence	±2 µm
long term stability	< 1 µm

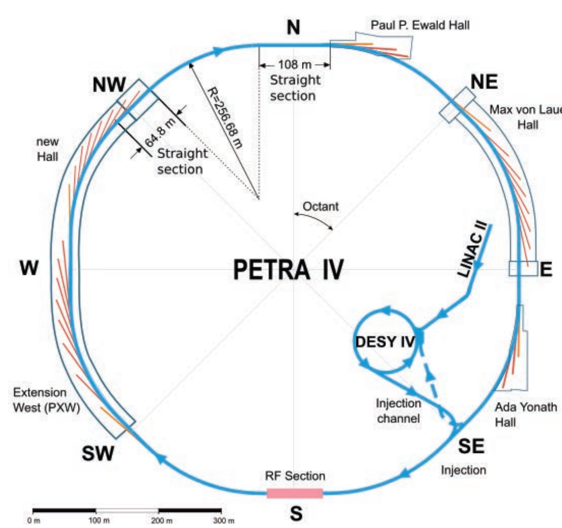

Figure 1: Layout of the PETRA IV facility.

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Different drift compensation schemes are available, the most popular one is the well proven concept of crossbar switching [9, 10] which is implemented in the *Libera* modules and stabilizes the analogue RF front–end part of the system. Another concept which has gained in popularity in recent years is the pilot tone (PT) compensation method where a sinusoidal PT signal with fixed frequency close to the carrier one is injected in the signal chain. This signal is used as reference for calibration and compensation, see e.g. Refs. [11–16]. If the PT signal is injected close to the BPM pickup before the cable, not only the front–end but also cable drifts can be compensated. However, the same effect can be achieved for crossbar switching if the analogue switching part is separated from the read–out electronics and brought as close as possible to the BPM pickup. In Ref. [17] both methods are discussed in detail and compared with each other. Based on this discussion and tests performed with the PT compensation scheme at PETRA III, it was decided to follow the idea with external crossbar switching.

This contribution summarizes first proof–of–principle measurements which were performed at PETRA III using a modified LB+ with an external switching matrix. These measurements indicate that the concept works well and that the performance of this modified test setup fulfills the specifications for PETRA IV.

TEST SETUP AT PETRA III

A sketch of the setup in use for the PETRA III studies is shown in Fig. 2. In order to get rid of the beam jitter, the four pickup signals from a test BPM in the tunnel are summed up with a combiner/splitter (MACOM DS-409-4), attenuated by a 500 MHz bandpass filter (Wainwright Instruments, WBK500-15-5SS), split again by the same type of combiner/splitter, and then fed to the switching matrix box. Outside the accelerator tunnel, the LB+ readout module is mounted in a rack located in an electronic hutch, the length

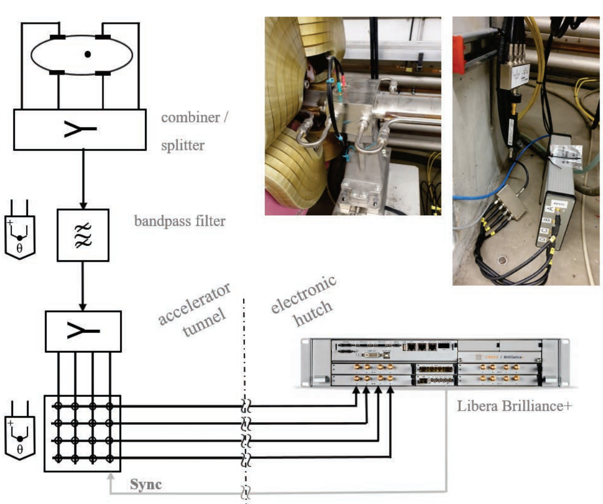

Figure 2: Principle scheme of the test setup. The photos show the setup in the tunnel: the BPM pickup (left) and the electronics part (right).

of the interconnecting cables (3/8” Cellflex, LCF38-50JFN) is about 100 m. In order to synchronize the external analogue crossbar switching with the digital one inside the LB+, both deviced are interconnected via a UTP Cat 7A cable. While the temperature in the electronic hutch is stabilized to a level of ± 1 deg, the accelerator tunnel at the BPM location is not stabilized and temperature drifts of more than 2 deg are possible throughout a week of operation. In order to measure the temperature at sensitive components, therefore both the external switching matrix and the bandpass filter are equipped with temperature sensors.

LONG TERM STABILITY STUDIES

Beginning from the end of April 2021 when the test setup was completed, a series of measurements was performed. Each measurement started at the end of a PETRA III maintenance day when beam was back in the machine, and stopped one week later at the beginning of the next maintenance day, i.e. the overall measurement time was about 160 h. As an example, Fig. 3 shows the temporal evolution of the beam current during one week of user run operation. About 50,000

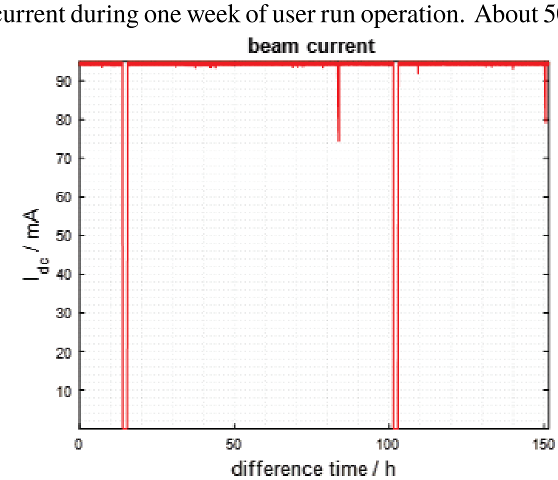

Figure 3: Beam current during one week of user operation end of May 2021. In this period PETRA III was operated with I_b = 95 mA in 40 bunches. In this week two total beam losses happened, and two times there was a delay in the top–up sequence.

data samples were recorded in Slow Acquisition (SA) mode of the readout electronics with 10 s wait time between consecutive samples. During the measurements, Digital Signal Conditioning (DSC) and crossbar switching were active in the LB+, the same holds for Automatic Gain Control (AGC).

Figure 4 represents the temperature profiles as measured with the two sensors mounted at switching box and bandpass filter. All data shown here and in the following were taken simultaneously to the ones in Fig. 3. As can be seen the tunnel temperature is not stable, in case of a beam loss it drops immediately by about 1 deg.

In Fig. 5 the position readout data from the SA data path are plotted. The monitor constant for data representation and beam position analysis amounts to $K_{x,y}$ = 10 mm throughout this report. In case of beam losses when there is no signal

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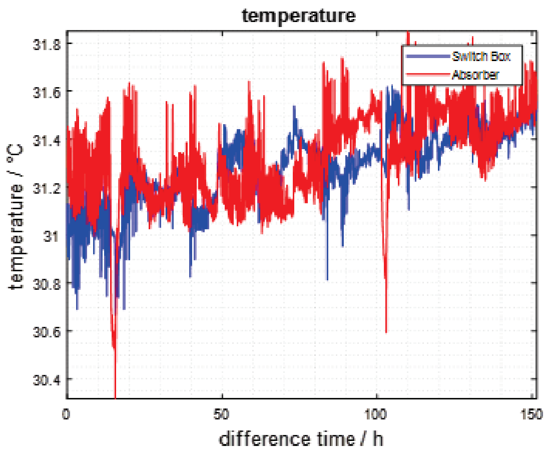

Figure 4: Temperature profiles measured at switching box and bandpass filter in the accelerator tunnel.

power at the input of the LB+, position readings are useless and a measure of the system noise. In order to exclude this distorting resolution influence, only data for $I_b \geq 25$ mA are considered for the data analysis.

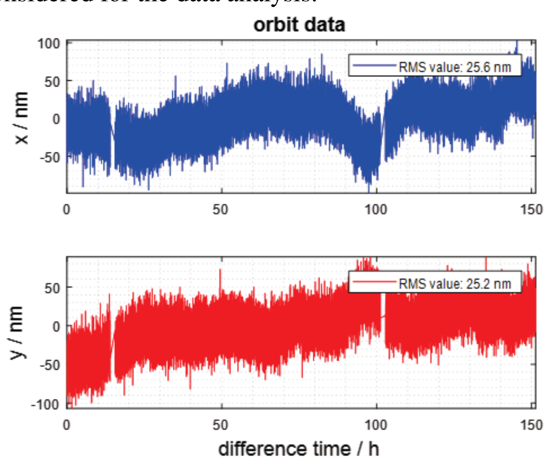

Figure 5: Position readings acquired from the SA data path. The monitor constant is $K_{x,y} = 10$ mm.

As can be seen from this figure, the long term stability of the position data is very good. The rms values amount to 25.6 nm horizontally and 25.2 nm vertically, the peak–to–peak readings are < 200 nm which is well below the requested specification of <1 µm. Furthermore, comparing Figs. 4 and 5 there is no obvious correlation between position readings and temperature profile, i.e. the compensation scheme by external crossbar switching works well and compensates temperature together with possible humidity changes on both readout electronics and interconnecting cables.

Figure 6 illustrates the temporal evolution of the DSC coefficients gain and phase which both characterize the complex channel gain. As can be seen, a change in the beam current (beam loss or delay in top–up sequence) is immediately visible in the gain, c.f. Fig. 3. However, after about 130 h all DSC gains show strong fluctuations which are neither directly correlated with a change in I_b nor with a temperature drift inside the accelerator tunnel. Correlating the rack temperature in the electronic hutch (not shown here) with the gain coefficients it was found that the rear door of the rack was opened at that time because of maintenance work, i.e. the DSC coefficients are very sensitive on environmental changes. However, it is important to note that no effect is visible in the position readings which means that this influence is well compensated.

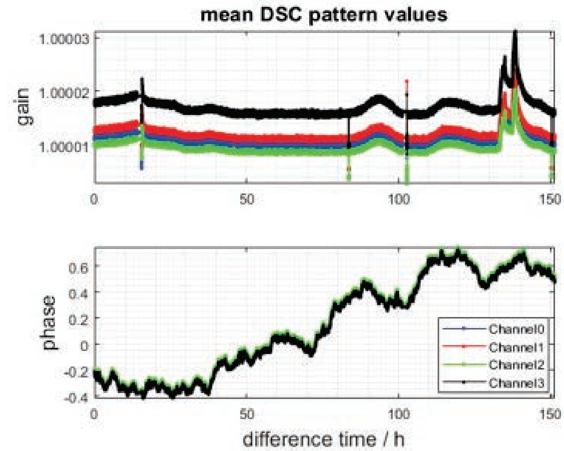

Figure 6: Temporal evolution of the DSC coefficients gain (top) and phase (bottom). Both parameters characterize the weighted average of the four data paths and represent a complex channel gain. More details about the theoretical background can be found in Ref. [9].

Besides the results presented here, other long term measurements were taken for both PETRA III operational modes (40 and 480 bunch filling pattern). All of them resulted in orbit rms values between 20 and 40 nm, thus giving confidence that the specification for the long term stability is fulfilled.

PERFORMANCE EVALUATION

Apart from the long term stability which is critical especially for PETRA IV due to the specific machine geometry, the remaining requirements listed in Table 1 were also subject of investigation. For the determination of the closed orbit resolution, 10 files of position readings were recorded both for Turn–by–Turn (TbT) and Fast Acquisition (FA) data path (PETRA III TbT frequency 130.1 kHz, FA data rate 10 kHz), each measurement consisting of 32768 consecutive samples. With knowledge of the sampling frequency, each position measurement was transformed in a corresponding Power Spectral Density (PSD), and taking into account that 10 data sets were recorded for each data path an averaged PSD was formed. Integrating the PSD over the frequency, the resolution can be determined as function of the bandwidth as shown in Fig. 7 for the FA data path. Below the first crossbar switching frequency at 3.3 kHz, the TbT measurement shows comparable results. As can be seen from this figure, at 1 kHz bandwidth the resolution is well below 100 nm, thus the specification is fulfilled.

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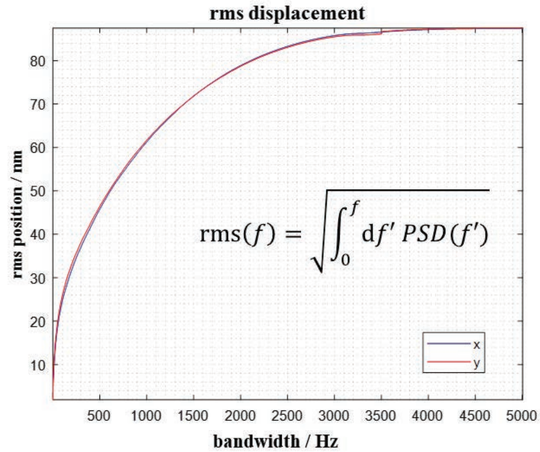

Figure 7: Closed orbit resolution as function of bandwidth for FA data path.

Figure 8 shows the single bunch (single turn) resolution as function of bunch current. For this measurement the data were collected from the Single Pass (SP) data path, i.e. in order to minimize resolution disturbing noise contributions a mask was set in the ADC spectrum which allowed to derive position information only from that region which contains bunch information. For the single turn measurement, a single bunch was injected in PETRA and dumped immediately after one passage. Each dot in the figure represents the rms from 100 consecutive shots. However, the bunch current from a single injection is not sufficient to test the specification at 0.5 mA. Therefore, single bunch measurements were also carried out with circulating beam at higher bunch currents using accumulation. As can be seen, for 0.1 mA bunch current both measurements agree well, therefore it is assumed that it is the case also for higher bunch currents, at least if no LB+ attenuator switching is involved which is the case for currents < 0.35 mA. While the resolution specification of <10 µm is reached already at this current, it is also the case for higher bunch charges.

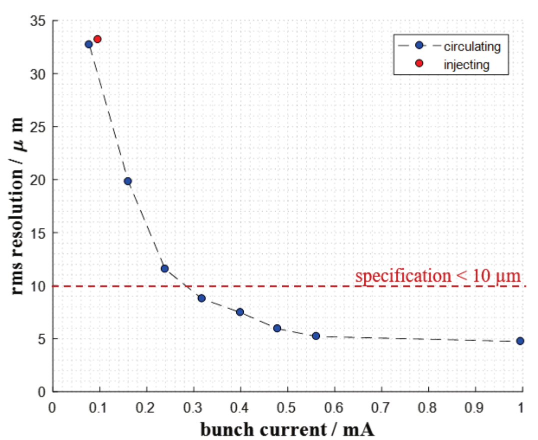

Figure 8: Single bunch resolution as function of bunch current for single turn (red dot) and circulating beam (blue dots).

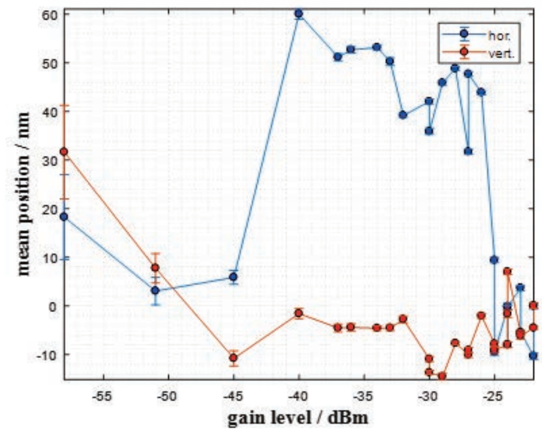

Figure 9: Beam position as function of input gain level (bunch current). Each dot represents the mean value from 500 SA position readings.

Finally the beam current dependency was investigated. PETRA III was filled with 120 mA in 480 bunches, then the beam current was reduced step by step by bringing collimator jaws closer to the beam. Position readings were recorded both in SA and TbT mode, Fig. 9 shows the result for the SA data path. As can be seen, the position variation is well below the specified ±2 µm level, the same holds for the TbT data not shown here. It should be noted that the gain variation with beam covers a range of only 40 dB and not 60 dB as specified. However, in order to protect the external crossbar switching matrix, higher gain levels were not possible. At the other hand, in the factory acceptance test without beam the same LB+ was investigated at higher power levels and demonstrating a similar performance, such that it can be concluded the same would be the case for a measurement with beam.

SUMMARY AND OUTLOOK

This paper summarizes first proof–of–principle measurements which were performed at PETRA III using a modified LB+ with external switching matrix. These measurements indicate that the concept works well, i.e. drifts in the RF front–end and from the interconnecting cables due to environmental changes are compensated to a high level. All long–term measurements performed so far indicate that the achieved readout stability is well below 50 nm (rms) over one week of operation, and independent from the bunch pattern. As demonstrated in laboratory measurements, the most temperature–drift critical element in the analogue signal chain is the external switching matrix itself: its temperature coefficient of about 72.5 nm/K dominates the temperature coefficient of the whole chain, therefore keeping the matrix at stable temperature is important. Furthermore, the overall performance of the readout electronics was investigated, indicating that it is comparable to a standard LB+ but with better long–term stability, thus meeting the specifications for PETRA IV. In the next step the readout system will be revised to be compliant with the MTCA.4 standard.

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