STUDIES FOR A BPM UPGRADE AT COSY

C. Böhme, M. Bai, F. Hinder, V. Kamerdzhiev, F.Trinkel
Forschungszentrum Jülich, Germany

Abstract

For the planned Electric Dipole Moment (EDM) precursor experiment at the COoler SYnchrotron (COSY) synchrotron and storage ring an accurate control of the beam orbit is crucial. The required beam position measurement accuracy demands an upgrade of the Beam Position Monitor (BPM) readout electronics. The BPM system currently in operation is described. The required performance and the possible upgrade scenarios are discussed.

INTRODUCTION

The COoler SYnchrotron (COSY) of the Forschungszentrum Jülich is a 184 m long racetrack-shaped synchrotron and storage ring for protons and deuterons from 300 MeV/c (protons) or 300 MeV/c (deuterons) up to 3.65 GeV/c. Built in are devices for stochastic as well as electron cooling. The stored ions can be polarized or unpolarized. Commissioned in 1993, some of the components are not only outdated, but start failing while spare parts for repair are hard to acquire. In addition, for the planned EDM [1] precursor experiment a higher beam position measurement accuracy is needed than can be reached with the used components. Therefore different upgrade scenarios are investigated.

CURRENT STATUS

COSY is equipped with 30 shoebox-style BPMs. During commissioning 27 BPMs of two types were installed, a cylindrical type with 150 mm diameter and a rectangular type 150 mm · 60 mm [2]. The selection was made to fit into the beam pipe, which is round in the straight sections and rectangular in the arcs in order to fit into the dipole magnets. Later on 3 BPMs were added, with special geometries to fit within the beam pipe of a different diameter close to experiments, giving a total number of 30. 2 of them are installed within the recently added 2 MeV electron cooler [3] and use their own electronic for readout, which is different from the others. One of them at the ANKE experiment, which uses a standard readout hardware. All other BPMs are read out by the same type of electronics [4], whose concept is shown in Figure 1. The readout electronic for each BPM, except for the pre-amplifiers, is housed in one VXI crate, consisting of 2 analog modules, 2 digital modules, one CPU, and one timing receiver. The pre-amplifiers are directly connected to the N-type vacuum feedthrough of the pick-ups. This pre-amplifier has a fixed gain of 13.5 dB with an input impedance of 500 $k\Omega$ and a bandwidth of 100 MHz. The gains and offsets of two pre-amplifiers have to be exactly matched for one plane of one BPM in order to avoid incorrect measurements. The preamplified signals are then fed into an analog module, where sum and delta signals are produced

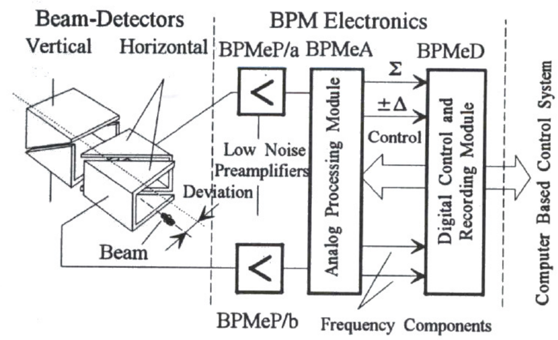

Figure 1: Current Beam Position Monitor electronics assembly [4].

using a hybrid. These signals are then treated separately and can be further amplified in 6 dB steps from 0 dB to 66 dB. Both the sum and the delta branches have two signal paths. A narrowband path features 3 possible filter settings with bandwidths of 10 kHz, 100 kHz, or 300 kHz and an additional amplifier that can be set from 0 dB to 18 dB in 6 dB steps. The broadband path with 10 MHz bandwidth can be used for turn-by-turn measurements while the narrowband signals are used for closed orbit measurements. The analog outputs are unipolar, the sign of the narrowband delta signal is detected separately and the information is transmitted by a separate TTL signal line. After the analog signal processing the signals are digitized in a digital module. This is done using 20 MHz 8 bit ADCs. For the narrowband signal the sampling frequency is lowered to 1 MHz or 100 kHz, depending on the selected analog bandwidth. For the sum signal only 7 of the 8 bits of the ADC are used, the 8th bit is used to indicate the polarity of the delta signal. The digital module generally has the possibility to buffer 4096 data points, while few modules can store up to 32768 data points for turn-by-turn measurements. The CPU of the VXI crate then calculates out of the narrowband signal the beam position using a scaling factor for the specific BPM geometry. It is also possible to transfer the raw data to the control system, display and export it.

LIMITATIONS OF THE CURRENT HARDWARE

First, the position measurement is highly dependent on the pre-amplifiers used for the two pick-up electrodes of one plain having identical characteristics, even better than usual production variations of electronic components. Therefore, at the time of construction, extensive tests have been performed to figure out identical pairs of the produced pre-amplifiers. Recent tests of selected pairs showed that the matching of the pairs is still good, even after years of opera-

ISBN 978-3-95450-176-2

tion. In addition, until now no defects were found for this part, so that there is no pressing need to replace those.

The analog modules have several issues [5]. They are failing at an increased rate, although until now most modules could be repaired. The modules require an extensive calibration procedures performed regularly, otherwise parameter drifts decrease the measurement accuracy . Therefore using an in situ calibration signal seems to be more promising than the calibration procedure by adjusting potentiometers.

The digital modules seem to be most outdated with only 8 bit sampling resolution, from which for the sum signal uses only 7 bits. The modules don't show a high failure rate so that the low resolution and the limited storage for turn-by-turn measurements are basically the main drivers of an upgrade.

As described above, the position calculation is done by the embedded CPUs. If introducing a calibration signal into the signal chain, the calibration data gathered has to be used for calculating the position. Here the hardware limitations, especially the low memory of the CPU modules, come into account, which does not allow the storage of larger lookup tables of correction values.

REQUIREMENTS

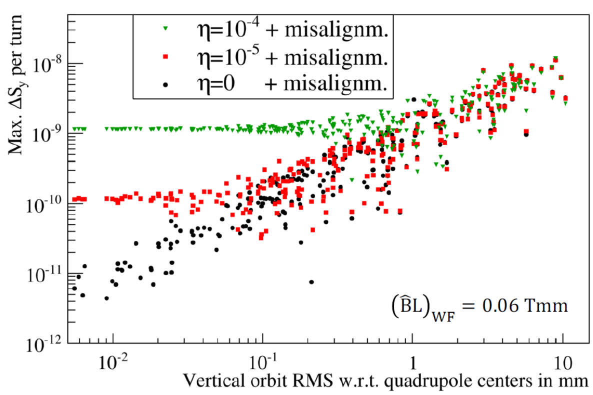

Figure 2: Calculated spin buildup per turn for different presumed EDM values. Depending on the real EDM value the beam has to be aligned in respect to the quadrupole magnets with a certain accuracy. This leads to the accuracy required from the BPMs [6].

Shown in Figure 2 is the required beam positioning accuracy of the EDM experiment for different presumed EDM values [6]. This accuracy reflects the possibility to align the beam in respect to the quadrupole magnets. In order to do this, the BPM accuracy is of cause only one part, other elements of the accelerator like the steering magnets are as well involved. As assumption a closed orbit measurement accuracy of 100 μm is the goal of the upgrade. The mechanical design of the COSY BPM does not support an accurate positioning of the pickups themselves e.g. by use of fiducial marks. A beam based alignment could reduce the BPM positioning uncertainty significantly and has to be considered.

UPGRADE SCENARIOS

Several upgrade scenarios have been discussed. In all scenarios some constraints have to be considered.

- The BPM pick-ups will remain unchanged, although they are not equipped with position markers, so their absolute position is only known within some error margin.
- Up to now no test signal for calibration purposes is used. In every upgrade scenario the introduction of test signals is mandatory.

Calibration Signal

Up to now the BPM system doesn't have a calibration signal path. Independent of the selected upgrade scenario, even if the old electronics will be kept, it appears crucial to inject a calibration signal in front of the pre-amplifier. The design of the calibration signal has to be adapted to the specific solution. While keeping the old analog electronics in place, with the early generation of the sum and delta signal, two test signals with variable amplitudes have to be provided. This is necessary for acquiring the gain and offset data for all possible gain settings in the delta and sum branches. A pure digital solution may only need one test signal that will be switched through the channels, in order to make sure the test signal will be identical for all channels.

To feed the test signal into the signal path, passive couplers or active switches are under consideration. With the advantage of the passive coupler, that it is less likely to fail, and the disadvantage, that during beam operation a calibration will not be possible. These facts have to be considered.

Another design choice under discussion is the central generation of a calibration signal vs. the local one. While a central signal generation can be performed with one high precision instrument, the distribution introduces signal variations from BPM to BPM. A local generation would have to be performed by a cheaper generator, here the later presented Red Pitaya board is under discussion, but will probably have a lower precision. In case of a purely digital solution, where only one signal is needed the local generation might be the better solution. When keeping the analog electronics in place, the two signals fed into it would have to be matched to each other and so a central generation might be the better solution.

Upgrade of the Digital Part Only

From the point of view of improving the performance of the BPM system an upgrade of the digital part seems to be the most urgent one. Furthermore, replacing the digital part only promises significant cost savings, as the amplifiers, both, the pre-amplifiers directly at the pick-ups and the ones in the analog modules, wouldn't have to be replaced, as shown in Figure 3. As candidate for a replacement a Red

ISBN 978-3-95450-176-2

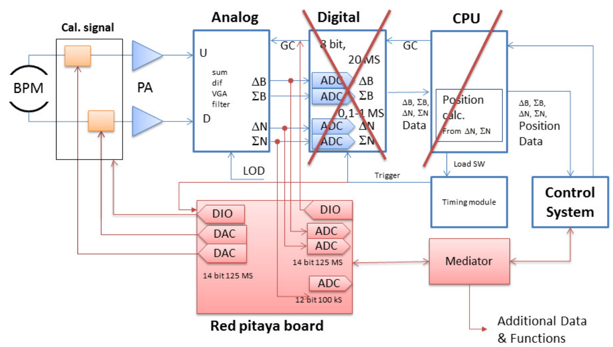

Figure 3: Concept of an upgrade, only replacing the digital part. Existing parts in blue, new parts in red. For the necessary trigger, the old CPU modules would have to be kept, as the timing modules require them during boot. All other functions of the old CPUs would be no longer used.

Pitaya board is under consideration. This board is a compact device featuring:

- $2 \cdot 125$ MS/s 14 bit ADCs with 50 MHz analog bandwidth
- $4 \cdot 100$ kS/s 12 bit ADCs
- $2 \cdot 125$ MS/s 14 bit DACs with 50 MHz analog bandwith
- $4 \cdot 100$ kS/s 12 bit DACs
- $16 \cdot$ digital I/Os
- Xilinx Zynq 7010 SoC FPGA
- GBit Ethernet communication

One could use one fast ADC for capturing of the broadband delta signal of the old analog module and the other one for the narrowband delta signal, but not for speed but for the 14 bit resolution. The sum signals will be captured by two slow ADCs. The two other ADCs will capture the TTL signals indicating the polarity of the delta signals. The 16 digital I/Os are used to set the amplification and filtering mode of the analog module. And finally, the 2 DACs will be used to provide a test signal to be fed into the signal chain in front of the pre-amplifiers in order to calibrate the signal chain.

Another candidate is using fast electronics from the CERN open hardware initiative. The philosophy there is to have carrier boards on which mezzanine cards for different applications can be attached. This way we could use VXI carrier boards to fit into our existing crates. A set of fast ADCs and digital I/Os could replace the old digital modules. There are existing projects with $4 \cdot 130$ MHz 16 bit ADCs, which could be used. On the carrier boards the possibility to use FPGAs is foreseen, giving the possibility to do complex calculations of the beam position in short times.

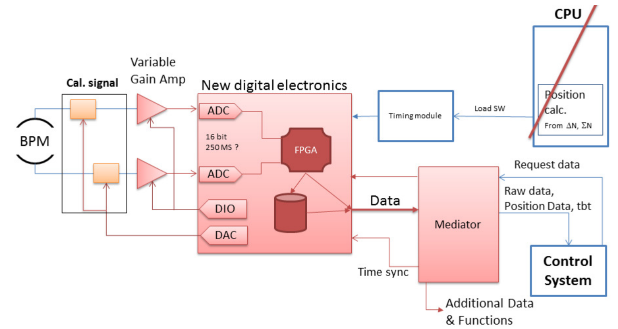

Figure 4: Concept of a complete electronics upgrade. Existing parts in blue, new parts in red.

Upgrade of the Entire System

Like other recently planned BPM systems e.g. [7, 8] the goal is to digitize the signals as early as possible in the signal chain. The downside of this upgrade scenario is that all components, including the pre-amplifiers, have to be replaced. The concept, as shown in Figure 4, is, that instead of the currently used fixed-gain amplifiers, variable gain amplifiers will be used in order to match the signal of the pick-ups to the input range of the ADC. Depending on the amount of stored particles and the beam energy, the induced voltage can range from hundreds of μV to tenths of mV. The input range of ADCs are usually in the range of up to 1 V. In order to use the resolution of the ADCs optimally, the signal should be amplified close to the this signal level.

After digitizing the individual pickup signals, further processing is done digitally. Usually an FPGA is used for real-time bunch detection, filtering and beam position calculation.

Several hardware options are under consideration:

- Instrumentation Technology Libera Hadron
- CERN Open Hardware
- DESY / XFEL / ESS solution based electronics

The Libera hadron platform was chosen for the BPM readout within the FAIR project [9]. Due to the fact that the Research Center Jülich is responsible for the design and construction of the HESR, the same hardware was chosen as a potential candidate for the COSY BPM upgrade as well. This approach insures an efficient use of resources. Unfortunately, while extensive tests with the Libera Hadron A were already performed, this device is no longer produced and is replaced by version B, which differs in design and features. The new Libera B is based on μTCA and is a modular system. Each chassis can host the electronics to read out 4 BPMs. The maximum sampling frequency is 250 MHz with 16 bit resolution. Most of the software provided by the manufacturer was build to FAIR specifications, with some extensions for other use-cases.

For the CERN open hardware the solution would be similar as the one described in the partial upgrade scenario, with

ISBN 978-3-95450-176-2

the difference that the analog amplifiers also would have to be replaced. Also the software component will be more complex, as the old analog electronics already provides a lot of the peak detection and filtering mechanisms.

Although not being identical, latest developments from DESY including XFEL and the ESS could be a prototype for a COSY solution. At least for the ESS case most of the designated hardware is commercially available, using Struck fast digitizer cards.

Control System Adaption

For all upgrade solutions, significant adaptions within the existing control system are necessary. Since the COSY control system is self-developed and outdated, evaluations are made if a modern control framework like Control System Studio (CSS) or FESA could be used as a mediator between the new electronics and the current control system to minimize the effort extending the existing control system. Within the current control system only features already existing for the old hardware would be available, while the full set of features would become available using the new framework. With this approach other accelerator sub-systems undergoing an upgrade in the future could as well use the new framework as mediator, replacing the control system currently in operation completely in a medium to long time frame.

CONCLUSIONS

Although the old electronics is performing within the specifications it was designed for, the much tighter specifications for the EDM precursor experiment require an upgrade of the BPM electronics. By introducing calibration signals, the uncertainties of the existing analog electronics can be minimized. A rather cost effective way would be to just replace the outdated digital part of the existing electronics. Nevertheless, the rate of failures of the analog modules increases. Therefore the need of a complete replacement becomes evident. The electron cooling capabilities of COSY demand for a BPM system capable of dealing with bunch lengths down to 20 ns. Current activities involve identifying a potential manufacturer of variable gain pre-amplifiers. Once the choice is made, test setups for different digital solutions will be performed in order to test their performance. As the time frame is rather short, the system should be ready for installation in late 2016, a solution providing the necessary software components might be preferred over a hardware where FPGA programming has to be done from scratch.

REFERENCES

[1] A. Lehrach on behalf of the JEDI Collaboration, “Beam and Spin Dynamics for Storage Ring Based EDM Search,” IPAC2015, Richmond, VA, USA, WEAB2.

[2] R. Maier et. al., “Non-Beam Disturbing Diagnostics at COSY-Jülich,” EPAC’90, Nice, France, June 1990, p. 800.

[3] V. B. Reva et. al., “Cosy 2 MeV Cooler: Design, Diagnostic and Commissioning,” IPAC2014, Dresden, Germany, MOPRI075.

[4] J. Biri et. al., “Beam Position Monitor Electronics at the Cooler Synchrotron COSY Jülich,” Eigth Conference on Real-Time Computer Applications in Nuclear Physics, Vancover, June 1993.

[5] F. Hinder et. al., “Beam Position Monitors @ COSY,” JEDI Collaboartion Internal Note, 13/2015, June 16, 2015.

[6] M. Rosenthal et. al., “Spin Tracking Simulations Towards Electric Dipole Moment Measurements at COSY,” IPAC2015, Richmond, VA, USA, THPF032.

[7] H. Hassanzadegan et. al., “System Overview and Current Status of the ESS Beam Position Monitors,” IPAC2014, Dresden, Germany, THPME166.

[8] K. Lang et. al., “Performance Tests of Digital Signal Processing for GSI Synchrotron BPMs,” PCaPAC08, Ljubljana, Slovenia, TUP002.

[9] M. Znidarcic et. al., “Hadron BPM For The FAIR Project,” IPAC2015, Richmond, VA, USA, MOPTY040.

ISBN 978-3-95450-176-2