COSY BPM ELECTRONICS UPGRADE

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Abstract

The Cooler Synchrotron COSY delivers proton and deuteron beams to the users since the early 90s. The experiments are carried out using the circulating beam as well as the beams extracted from the ring and delivered by three beamlines. The original BPM system still operational in the ring does not fulfill the requirements for new experiments. It utilizes cylindrical and shoe-box type diagonally cut capacitive pick-ups. The most signal processing is done the analog way. Additionally to its age and the increasing failure rate, the analog processing introduces large drifts in e.g. the offset, which regularly require a significant effort for manual calibration. Even then the drifts render it impossible to match the requirements of the planned JEDI experiment, which is an orbit with a maximum of 100 μm RMS deviation. Therefore an upgrade of the readout electronics was decided. The decision process is described, the implications listed and the current status is reported.

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 600 MeV/c (deuterons) up to 3.7 GeV/c. Built in are devices for stochastic as well as electron cooling. The stored ions can be polarized or unpolarized. Commissioned in 1993, the electronic parts of the BPM system are not only outdated, but start failing while spare parts for repair are hard to acquire.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 for the BPM system were investigated.

CURRENT STATUS

COSY is equipped with 29 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. Recently 2 BPMs were added with special geometries to fit within the beam pipe of the 2 MeV electron cooler [3]. These two use their own electronics for readout, which is different from the others.

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

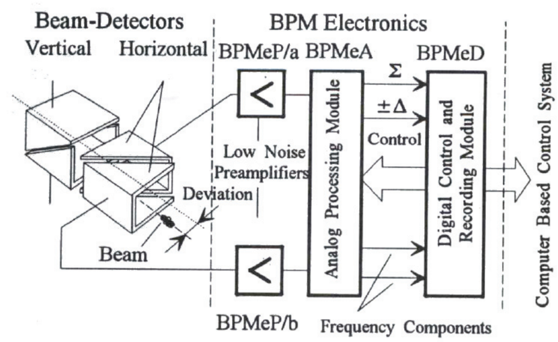

Figure 1: Current Beam Position Monitor electronics assembly [4].

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 (-3 dB). 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 fed into an analog module, where sum and delta signals are produced 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 capability to buffer 4096 data points, while few modules can store up to 64k data points that can be used for turn-by-turn measurements. The CPU in the VXI crate 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 broadband data to the control system display and export it, for e.g. computation of the turn-by-turn position.

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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 component pairs with identical characteristics. Recent tests of selected pairs showed that the matching of the pairs is still good, even after years of operation. In addition, until now no defects were found for this part, so that there is no pressing need to replace the preamplifiers.

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 on the testbench.

The digital modules seem to be the 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

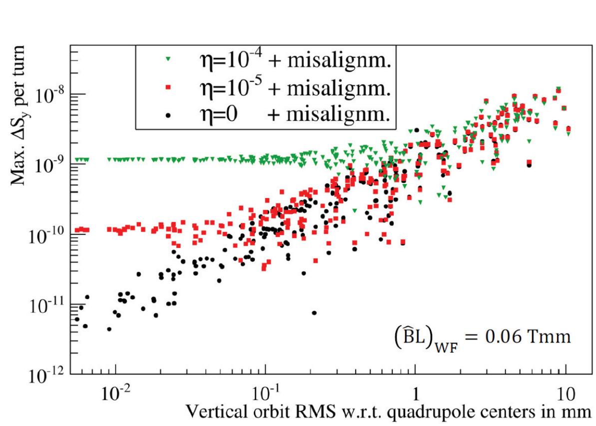

Figure 2: Calculated spin buildup per turn for different presumed EDM values. Depending on the real EDM value the beam has to be aligned in respect to the quadrupole magnets with a certain accuracy. This leads to the accuracy required from the BPMs. [6].

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 with respect to the quadrupole magnets. In order to do this, the BPM accuracy is of course only one part, other elements of the accelerator like the steering magnets are as well involved. As assumption a orbit with a maximum of 100 μm RMS deviation 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 BOUNDARIES

Several upgrade scenarios have been discussed. In all scenarios some common 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 it appears crucial to inject a calibration signal in front of the pre-amplifier. The generation of the calibration signal and the distribution is still under discussion. A solution may only need one test signal that will be switched through the channels or being splitted by passive elements, 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 but will probably have a lower precision.

Readout Electronics Upgrade

Like other recently planned BPM systems [7, 8] the goal is to digitize the signals as early as possible in the signal chain.

Several hardware options have been considered:

- Instrumentation Technology Libera Hadron

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- System based on Spectrum M4I.4421-X8 high speed digitizer
- DESY / XFEL / ESS solution based electronics based on the μTCA4 standard
- National Instruments solution similar to SNS upgrade [9]

The Libera hadron platform was chosen for the BPM readout within the FAIR project [10]. 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. 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.

A system based on a Spectrum M4I.4421-X8 high speed digitizer was evaluated. The digitizer features four 16-bit 250 MHz ADCs. The card features a switchable input range from ±0.2 V to ± 10 V. This feature would probably lead to the fact that the pre-amplification could remain untouched with the existing 13.5 dB fixed gain amplifiers, except of course the introduction of a calibration signal. The digitizer is in form of an 8 lane PCIe card. The processing of the signals would in this case, unlike all other solutions, not be done in a FPGA but in the processor of the hosting PC.

Although not being identical, latest developments from DESY including XFEL and the ESS, based on the μTCA4 standard, could be a prototype for a COSY solution. At least for the ESS case most of the designated hardware is commercially available, e.g. Struck fast digitizer cards.

Another possibility investigated was the solution proposed for a BPM readout electronic upgrade at SNS [9]. There National Instruments ADCs and FPGA modules are used for the processing of the signals. This decision was taken because with the NI hardware the FPGA used for processing can be programmed using the NI graphical programming framework LabView.

Decision After a recommendation of a review committee late 2015 the decision was made to prefer the Instrumentation Technology Libera Hadron system for an upgrade. This decision was made because of the timeline of the EDM precurser experiment and that the LIBERA brings a tested software collection for signal processing, while all other solutions would have implicated the own development of software for readout and position calculation. Furthermore, the efficient use of resources, by only using one system in both projects of the IKP, COSY and HESR, emphasized that decision.

This decision came along with two other results. First, as the input range of the LIBERA can not be switched, a switchable amplifier has to replace or to be added to the fixed-gain pre-amplifiers now used. The second decision made was to use the EPICS protocol for further extensions or replacements of accelerator parts, with the goal to completely switch to an EPICS based control system in the long term. Although still in the evaluation, it is highly probable that the Control System Studio (CSS) framework will be used along with EPICS.

FIRST MEASUREMENTS WITH LIBERA HADRON

In order to start integration of the LIBERA Hadron one system was already bought and is under test. The shown results are the result of tests with the hardware to evaluate the complete signal chain.

Pre-Amplifiers

As described already, the input of the LIBERA system is with a fixed input range. Therefor the necessity of switchable amplifiers is seen, in order to utilize the input range as complete as possible. For testing purposes 4 FEMTO DHPVA-100 switchable amplifiers were ordered including a custom modification to an input impedance of 500 kΩ. The gain is switchable in 10 dB steps between 10dB and 60 dB. Figure 3 shows a measurement of a COSY beam taken at

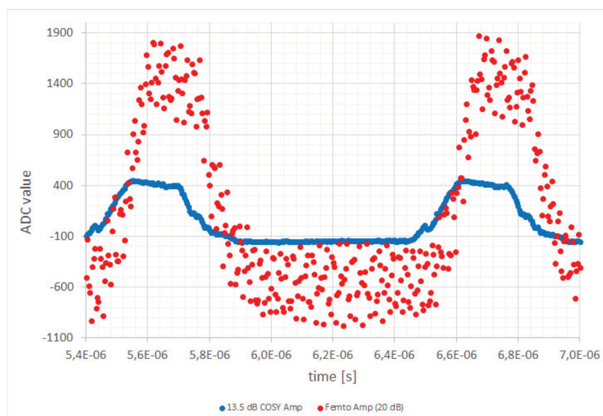

Figure 3: Measured signal using the LIBERA Hadron ADCs for beam in COSY. While using the traditional COSY fixed gain amplifiers the noise is much lower compared to switchable amplifiers bought for testing purposes and modified from the producer to an input impedance of 500 kΩ.

the same time at two neighboring BPMs. One was equipped with the traditional 13.5 dB fixed gain amplifier while the other used the switchable FEMTO amps, in this case set to a gain of 20 dB. Calculating the RMS value between two bunches, the traditional COSY amp has a value of 150 while the FEMTO has a vale of 600, both in ADC raw values. Because of this behavior the selection process for a new amplifier is still ongoing. A possible alternative to replace the traditional amps completely might also be to keep them in place and add a second stage amplifier with a switchable gain.

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Beam Noise Measurements

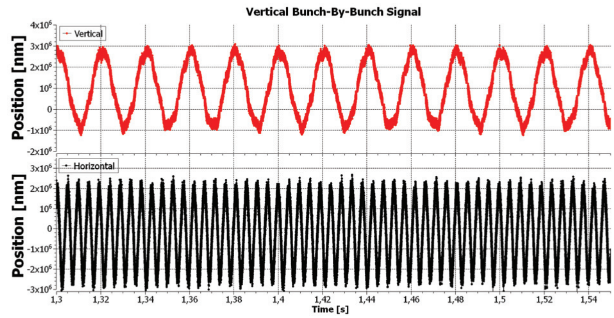

Figure 4: Measured bunch-by-bunch position of the COSY beam. The measurement shows a beam oscillation of 50 Hz in the vertical plain and one with 200 Hz in the horizontal plain. The calibration of the measurement system to the calculated position of the beam has not been verified yet, therefor the absolute position of the beam might be scaled by a unknown factor.

While running test measurements to familiarize ourselves with the LIBERA Hadron functions, a noise in the beam position could be observed. With the traditional BPM system only narrowband measurements slower than 1 Hz are possible or the observation of the broadband ADC raw data. From this data a bunch-by-bunch position would have to be calculated manually, with the amount of stored data point, being up to 4096 at 20 MHz, only very few bunches can be stored. In the recorded data the beam shows an oscillation in the vertical plain of 50 Hz and in the horizontal plain with 200 Hz. The calibration of the LIBERA system towards the geometrical properties of the BPM has up to now not been cross-checked, therefor a constant factor might have to be applied to the beam position data shown in Figure 4. This behavior requires further examination.

CONCLUSIONS

Although the old electronics is still performing within the specifications it was designed for, the much tighter specifications for the EDM precursor experiment require an upgrade of the BPM electronics. The LIBERA Hadron system was recommended for the upgrade by an expert committee. In the meantime several options for the pre-amplifier system are investigated to match the input range of the LIBERA system to the BPM signals with different beam properties. Within the design a calibration signal is envisaged as well, which is not available up to now. In addition the decision was made to use the EPICS standard as future base for the control system. Some test measurements were showing new aspects of the beam behavior not seen with the old system and its standard GUI. These behavior has to be examined further.

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