ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-TUPCF20

COSY ORBIT CONTROL UPGRADE

C. Böhme, I. Bekman, V. Kamerdzhiev, B. Lorentz, S. Merzliakov, M. Simon, C. Weidemann
Forschungszentrum Jülich, Germany

Abstract

The Cooler Synchrotron COSY can store and deliver proton and deuteron beam in the momentum range from 0.3 GeV/c to 3.65 GeV/c for internal and external experiments. New requirements of the Jülich Electric Dipole Moment Investigation (JEDI) experiment requires a RMS beam orbit distortion smaller than 100 μm. This requirement lead so far to the replacement of the BPM readout electronics, an introduction of a slow beam orbit correction and feedback system and the re-alignment of the magnets. All three projects are close to completion, therefore first results are presented.

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 0.3 GeV/c (protons) or 0.6 GeV/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, the machine was mainly used for target experiments. Therefore no special focus was laid on the beam orbit, as long as the target overlap was maximized.

With the JEDI (Jülich Electric Dipole moment Investigations) experiment new requirements concerning the overall RMS beam orbit deviation were introduced [1]. Therefore an automatized beam orbit control system was developed. Furthermore other components were identified being in need to be upgraded or to be added. One example is the analog BPM readout electronics, which offsets prevents an accurate position determination especially around the 0 position. Another example is the positioning of the magnets, which drifted out of their position over the years [2].

BPM SYSTEM

COSY is equipped with a total of 33 BPMs whereas 29 are shoebox-style BPMs utilizing a standard readout electronics. During commissioning of COSY 27 BPMs of two types were installed, a cylindrical type with 150 mm diameter and a rectangular type with 150 mm · 60 mm inner size [3]. 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 4 BPMs were added with special geometries. Two of them are designed to fit within the 2 MeV electron cooler [4]. Another 2 are based on Rogowski coils in order to have a minimal longitudinal length for the Wien Filter of the JEDI experiment [5]. These four use their own, non-standard electronics for readout.

Analog BPM Signal Processing

At the commissioning of COSY, a BPM readout system was build based on a mainly analog processing [6]. 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 kΩ and a bandwidth of 100 MHz (-3 dB). The gains and offsets of two pre-amplifiers have been exactly matched for one plane of one BPM in order to avoid incorrect measurements. The preamplified signals are fed into an analog processing module, where sum and delta signals are generated 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. A broadband path with 10 MHz bandwidth can be used for direct sampling of the signals. 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 separate 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. The CPU in the VXI crate calculates out of the narrowband signal the beam position. It is also possible to transfer the raw broadband data to the control system in order to display and export it, for e.g. computation of the turn-by-turn position.

Despite the outdated digital hardware and the increasing failing rate, the main issue lays within the split signal path of the differential signal and the sign of the position. An offset of the differential signal is measured on all modules, even directly after calibration. Because of this the measured beam position never reaches the zero position [7]. Using the introduced orbit correction system this leads to incorrect correction settings.

Digital BPM Signal Processing

Because of these problems with the analog BPM signal processing system, a new system was introduced with digital signal processing. The decision was made to utilize the commercially available Libera hadron system [8]. The system was recently put into operation and commissioning is ongoing. First results are presented later in this article.

ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-TUPCF20

The system samples the input signal with a 250 MHz 16 bit ADC without further analog signal processing. From the digitized signals the Libera Hadron derives several data sets:

- The ADC raw data can be stored in a 2GB dedicated memory, which allows the readout of about 1 second of data.
- The bunch by bunch information is stored in another dedicated 2 GB memory, which allows at COSY the storage of about 1 minute of turn by turn data, depending on the beam's revolution frequency.
- Based on the bunch by bunch data a FFT analysis is performed, allowing tune measurements.
- An integrated 10 Hz continuous bunch position information is streamed out of the system.

Amplifiers

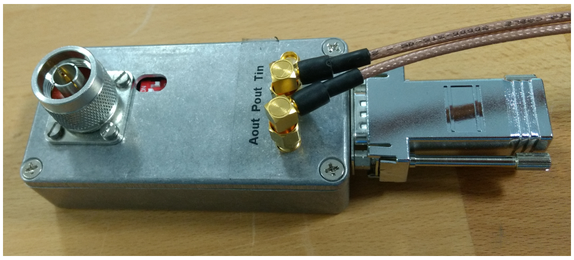


Figure 1: Newly developed amplifier for connection directly to the pick-ups. The amplifier features a signal output after a fixed gain pre-amplifier of 13.5 dB or 20 dB (selectable via switch), a second output after two additional adjustable gain amplifier stages and a calibration signal input. On the right side in the picture a connector for the supply voltages and the gain control signals is located.

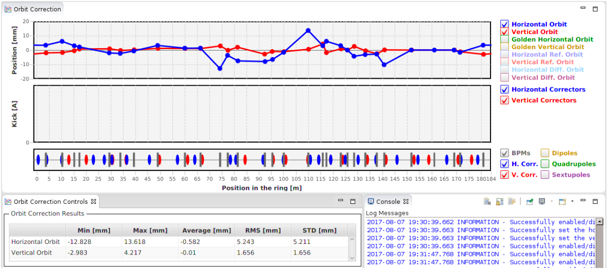
The input of the Libera system has a fixed input range. Therefor the necessity of adjustable gain amplifiers was seen, in order to cover the beam intensity range of COSY while achieving the best possible beam position resolution. The former BPM system used a fixed-gain pre-amplifier directly attached to the pick-ups and switchable amplifiers within the BPM electronics. This system showed the disadvantage if only a pre-amplified signal is conveyed over the connecting cables, which resulted in increasing noise levels with cable length. To overcome this disadvantage, the former BPM electronics was re-located close to the pick-ups into the accelerator tunnel. With this in mind in the new system a tradeoff was made: The main amplification was located in the amplifiers directly connected to the pick-ups, allowing longer cables with a better signal to noise ratio, but with the disadvantage of more complex electronics being located in the tunnel compared to a fixed-gain amplifier. The Amplifiers consist of three stages:

- 1st stage: a fixed gain amplification with 13.5 dB or 20 dB, defined by dip-switches.
- 2nd stage: a continuously adjustable amplifier with 0 dB to 50 dB amplification
- 3rd stage: a continuously adjustable amplifier with -20 dB to 10 dB amplification

The amplifier has 2 output paths, as shown in Fig. 1. The first output is after the first fixed-gain stage, in order to connect to the analog BPM electronics to keep the usual functionality during the commissioning process. A second output after all three stages is connected to the digital BPM electronics. A third connector features a calibration signal input, which is fed into the 1st stage with a 50 dB signal attenuation.

The amplification of the 2nd and 3rd stage are controlled with an analog voltage. The control is realized utilizing a Beckhoff Ethercat system. A 0 V to 10 V DAC controls the second stage of all 4 amplifiers of one BPM together. The third stage is controlled individually for each amplifier using a 0 mA to 20 mA DAC, which is transformed in the amplifier to a voltage control signal. The connection to the control system is done with DLS-ethercat from Diamond Light Source [9]. Tests of the amplifier showed an input noise of 1.4 nV/$\sqrt{Hz}$ at 10 MHz. The gain control scheme is designed to allow gain control resolution of 0.001 dB (which translates to the μm level in terms of beam position).

ORBIT CONTROL



Orbit Correction Results

	Min [mm]	Max [mm]	Average [mm]	RMS [mm]	STD [mm]
Horizontal Orbit	-12.828	13.618	-0.582	5.243	5.211
Vertical Orbit	-2.983	4.217	-0.01	1.656	1.656

Log Messages

```
2017-08-07 19:30:39.662 INFORMATION - Successfully enabled/di
2017-08-07 19:30:39.663 INFORMATION - Successfully set the hc
2017-08-07 19:30:39.663 INFORMATION - Successfully set the ve
2017-08-07 19:30:39.663 INFORMATION - Successfully enabled/di
2017-08-07 19:31:47.768 INFORMATION - Successfully enabled/di
2017-08-07 19:31:47.768 INFORMATION - Successfully enabled/di
```

Figure 2: GUI of the orbit control system developed in cooperation with Cosylab d.d. The GUI can be used for orbit position visualization (mode shown) and for orbit correction towards a configurable orbit. In the most upper part the actual orbit measurement is shown, beyond the actual settings of the correction magnets is displayed when in orbit correction mode. For reference the position of the BPMs and magnets can be visualized in the part below. The GUI also automatically calculates the RMS orbit deviation and displays it. Control buttons for e.g. activation of the orbit correction are not shown in the picture.

In cooperation with Cosylab d.d., an orbit control system was introduced [10]. The GUI of this system is shown in Fig. 2. This system is operational since late last year and initially interfaced with the analog BPM system and the function generators, controlling the corrector magnets power converters. Using the analog BPM system as base for the orbit correction, the speed of the system is limited to the reaction time of the system, which allows about one measurement

ISBN: 978-3-95450-192-2 doi:10.18429/JACoW-IBIC2017-TUPCF20

every 4 seconds. The system uses an iterative process to correct towards the desired orbit, with the correction strength adjustable. A result of the orbit control mechanism is shown in Fig. 3. In this example the systems tries to put the orbit to zero at all BPMs, resulting in an overall RMS value of about 1.6 mm.

The system was build in the perspective, that the BPM readout system will be replaced. Therefore the communication to the BPM electronics and the correction magnets controllers was done utilizing the EPICS protocol and a program module doing the actual interfacing between the EPICS protocol and the self developed command interface of the analog BPM system and the correction magnet controllers. By adapting the EPICS variables to the digital BPM readout system, the orbit correction system can utilize the data of the digital system without changing the core functionality. This was successfully implemented. The modification was made utilizing the 10 Hz continuous position data stream.

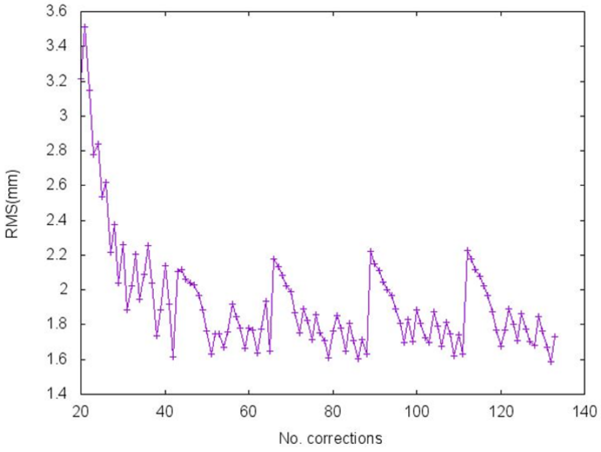


Figure 3: Example of the RMS orbit with activated orbit control towards a zero orbit using the analog BPM system, which, because of offsets, gives false values around the zero position. The RMS is reduced to about 1.6 mm. The spikes every 25 correction cycles are the result of a new beam injection.

CURRENT STATUS

- All 29 standard BPMs have been connected to the digital BPM signal processing system. This includes the new amplifiers.
- 8 Libera Hadrons have been successfully put into operation. The necessary signals like trigger signals or RF reference are connected from a single point with equally long cables.
- First measurements with the digital BPM readout system were performed and ADC raw data, bunch by bunch data and slow position data were successfully measured.
- The connection between the Ethercat master and the EPICS control utilizing the DLS-ethercat package was at the point the presented data was recorded not fully functional, so temporary the control was realized using a HTML page. It is successfully implemented in the meantime.
- The orbit control software was adapted to work with the digital BPM readout system, which was successfully tested.

FIRST MEASUREMENTS

First measurements were performed using different beam settings. The beam intensity was varied to test different settings of the amplifiers. Local orbit bumps were introduced to check the performance of the readout system and an Orbit Response Matrix was measured to check for wrongly cabled BPMs. Fig. 4 shows an example of an ADC measurement for one BPM with about 10^{10} particles stored and a low gain of the amplifiers. This results in a rather high signal level with relatively low noise.

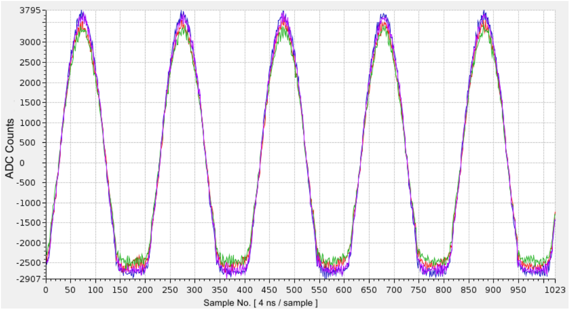


Figure 4: Example of the ADC measurements for all four pick-ups of one BPM.

To compare performance, the amount of stored particles was reduced to $5{\cdot}10^8$ particles. The BPM with the most noise is shown in Fig. 5 as an example. This was measured with a total amplification of 55 dB, with a maximum of 80 dB possible. The other BPMs had a much lower noise level, so that it can be expected that the position measurements will also work with an even lower amount of stored particles. The noise level was significantly reduced later on by resolving a grounding issue within the amplifier enclosure.

CONCLUSIONS

To match the requirements of the EDM precursor experiment, an automated orbit control system was introduced, in order to minimize the overall beam orbit RMS deviation down to 100 μm. In this context the performance of the analog BPM signal processing was found to be causing issues, as described above. Therefore an upgrade to the BPM signal processing system was done using the Libera Hadron. Because of the fixed input parameters of the Libera Hadron new amplifiers were developed in-house. The gain control of this amplifiers was done using an Ethercat system which is controllable through the EPICS control system protocol.

The whole system was put into operation end of July this year and first measurements were performed successfully.

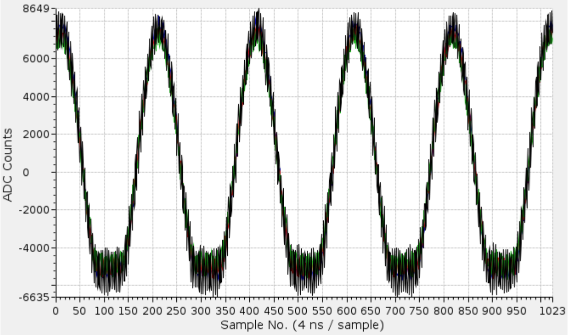


Figure 5: ADC measurement with a rather low amount of stored particles, about $5{\cdot}10^8$. All 4 pick-up signals of the most noisy BPM are shown. The noise level was significantly reduced later on by resolving a grounding issue within the amplifier enclosure. This gives room for position measurements with an even lower amount of stored particles.

OUTLOOK

Although the new BPM readout system was put into operation, the signal generators providing the calibration signals were not yet installed. The hardware as well as the corresponding software will be commissioned within a few months. An automatic gain calibration on a daily basis is envisaged for the system.

One power supply is used to power up to 8 amplifiers. Short circuit protection based on a specialized integrated circuit was implemented for individual channels. High failure rate of the protection circuitry was observed during the commissioning phase. A new design is on the way.

As described before, mainly the 10 Hz output of the Libera Hadron system is used for operation. The EPICS transfer of this information stops several times a day, therefore a more stable mode of operation has to be found.

In addition, the EPICS position information could be quickly implemented into the earlier designed orbit control system. But for a full integration the control of the Libera Hadron will be implemented in the system.

REFERENCES

[1] M. Rosenthal *et al.*, “Spin Tracking Simulations Towards Electric Dipole Moment Measurements at COSY”, in *Proc. IPAC’15*, Richmond, VA, USA, May 2015, THPF032.

[2] V. Schmidt *et al.*, “Analysis of Closed-Orbit Deviations for a First Direct Deuteron Electric Dipole Moment Measurement at the Cooler Synchrotron COSY”, in *Proc. IPAC’17*, Copenhagen, Denmark, May 2017, TUPVA083.

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

[4] V. B. Reva *et al.*, “COSY 2 MeV Cooler: Design, Diagnostic and Commissioning”, in *Proc. IPAC’14*, Dresden, Germany, June 2014, MOPRI075.

[5] J. Slim *et al.*, “Design of the electrical circuit of the new RF Wien Filter at COSY-Jülich”, 22nd International Spin Symposium, Champaign, IL, USA, September 2016.

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

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

[8] C. Böhme *et al.*, “Cosy BPM Electronics Upgrade”, in *Proc. IBIC’16*, Barcelona, Spain, September 2016, TUPG26.

[9] R. Mercado *et al.*, “Integrating Ethercat Based IO into EPICS at DIAMOND”, in *Proc. ICALEPCS’11*, Grenoble, France, October 2011, WEMAU004.

[10] M. Simon*et al.*, “COSY Slow Orbit Feedback System”, in *Proc. IPAC’17*, Copenhagen, Denmark, May 2017, TUPIK050.