# COSY SLOW ORBIT FEEDBACK SYSTEM

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*Abstract*

The Cooler Synchrotron (COSY) [1] at Forschungszentrum Juelich is currently carrying out the preparation for a direct measurement of the Electric Dipole Moment (EDM) of the deuteron using an RF Wien filter [2, 3]. In a magnetic storage ring with the spin vector aligned along the direction of motion, the EDM manifests in a buildup of the vertical spin component. Besides this signal, radial magnetic fields due to a distortion of the vertical closed orbit can produce a similar signal. This signal is a systematic limit of the proposed measurement procedure. Based on simulation studies [4], a vertical closed orbit distortion with a RMS smaller than 0.1 mm is required to achieve a sensitivity of $10^{-19}$ e.cm. Since current orbit distortions amount to about 1.6 mm an orbit correction feedback system was proposed and implemented.

## INTRODUCTION

The synchrotron and storage ring COSY accelerates and stores unpolarized and polarized proton or deuteron beams in the momentum range between 0.3 GeV/c and 3.65 GeV/c. COSY possesses high flexibility with respect to ion optics and is specialized on beam cooling. For this purpose two electron coolers, namely a 100 kV cooler for proton momenta up to 0.6 GeV/c and a 2 MV cooler for up to maximimum COSY momentum, and stochastic cooling for proton momenta above 1.5 GeV/c are operated. Theses features are the reasons why COSY was proposed to serve for the first precursor experiment on the direct measurement of the Electric Dipole Moment (EDM) of the deuteron (see [5] and references within). The systematic limit of the proposed measurement is dominated by distortions of the vertical closed orbit. This paper describes the efforts and achievements towards reducing the present orbit distortions by means of a newly implemented slow orbit feedback system.

## ORBIT CORRECTION ALGORITHM

The developed closed orbit correction scheme is based on the orbit response matrix (ORM), which contains thousands of data points reflecting the focusing structure of the ring [6]. The closed orbit ORM is defined by:

$$\begin{pmatrix} \vec{x} \\ \vec{y} \end{pmatrix} = M_{\text{ORM}} \cdot \begin{pmatrix} \vec{\Theta}_x \\ \vec{\Theta}_y \end{pmatrix}, \tag{1}$$

where $(\vec{x}, \vec{y})$ are the measured horizontal and vertical shifts of the closed orbit at all beam position monitors (BPMs) for a change in the deflection strength of the steering magnet by $(\vec{\Theta}_x, \vec{\Theta}_y)$.

Thanks to recent efforts, an ORM of COSY can nowadays be automatically measured [7], derived using a MAD-X based software tool or simply calculated by

$$M_{i,j} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi\nu} \cdot \cos(|\phi_i - \phi_j| - \pi\nu) + \frac{D_i D_j}{\eta L_0}, \tag{2}$$

where the second term only applies in case of the horizontal orbit. Here, $\beta$ are the betatron amplitudes at the position of the BPM $i$ and the corrector magnet $j$, $|\phi_i - \phi_j|$ is the corresponding phase advance between the elements, $\nu$ is the transverse betatron tune, $D$ is the dispersion, $\eta$ is the phase slip factor, and $L_0$ the circumference of the ring. Direct calculation of the matrix elements of course only gives access to the non-coupling terms of the ORM.

A singular value decomposition (SVD) is than utilized to invert the ORM, which, multiplied to the uncorrected orbit, yields the appropriate kick angles of the corrector magnets:

$$\Delta \begin{pmatrix} \vec{\Theta}_x \\ \vec{\Theta}_y \end{pmatrix} = M_{\text{ORM}}^{-1} \cdot \begin{pmatrix} \vec{x} \\ \vec{y} \end{pmatrix}_{\text{uncorrected}}. \tag{3}$$

Applying only fractions of the calculated kick angles in multiple iterations enables a gradual improvement of the orbit distortion. During a regular COSY cycle of several hundred seconds the orbit can now be remeasured with a chosen frequency and corrected using the once derived ORM.

## OVERVIEW COSY AND ACTUAL SYSTEM

Cosy was planned in the late 80s and build in the early 90s. It was constructed as a feed forward machine because of the typical limited computing power of that time. Therefore a complete machine cycle setting is calculated beforehand and loaded to the magnet controllers, which, after a trigger signal, run their program with only a possibility for an emergency abort. A manual operation of the controllers (DC Mode) was not used so far, but initially implemented.

The COSY BPM system is based on analog processing using a hybrid for sum / difference. Thereafter the signals are filtered using an analog system and then sampled using an 8 bit 20 MHz ADC. The ADCs sampling frequency is reduced in dependence of the filter settings, to 1 MHz or 100 kHz. For closed orbit measurements a filter of 300 kHz bandwidth and a sampling rate of 1 MHz is used. The analog voltage of the sum and difference signals is always positive. For the difference signal the sign is determined in a phase

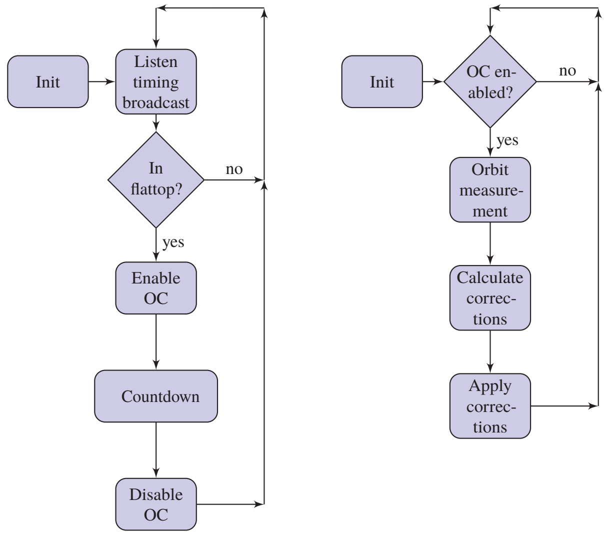


Figure 1: Block diagram of the orbit cycle control (left) and the orbit correction algorithm (right).

comparator and transmitted via a TTL signal to the digitizer. There one bit of the sum signal is used to indicate the difference signal's sign, thus resulting in only 7 bits being used for the sum signal. This method is fragile to offsets of the analog processing. An offset of the difference signal results in the effect, that the calculated beam position jumps around the zero position, never reaching it. Another source of inaccuracy is the amplification of the system. As the ADCs have a rather low dynamic range, the signal has to be amplified in fine steps, a total of 18 steps with 6 dB difference each. Therefore a lot of switchable amplifiers have to be present, with each having it's own deviations from the nominal value. Consequently, a calibration of all amplification stages for all BPMs would have to be performed to acquire exact results. The calculation of the beam position is done in the local VME CPU to minimize the network load of the coaxial line (Cheapernet) ethernet. This would require a local use of these calibration values, which the used CPUs can't store because of low memory.

The magnets controller has an 11 bit parallel interface connected to the VME controllers, which are not synced to each other. If used in the before mentioned DC mode the speed of the magnet value change is 1 bit per ms resulting in roughly 2 seconds for 100% of output change. The magnet power supplies can typically deliver ±30 A. The power supply accuracy is in the region of 30 mA, therefore just replacing the DAC would not result in a better accuracy.

## IMPLEMENTATION

A typical cycle starts with injection, followed by synchronous ramping of the magnets during which the beam acceleration takes place. While ramping, the steerer and dipole magnets are controlled by a function generator that follows pre-loaded waveforms. The direct current control required for the orbit correction to take place during the cycle is only possible when the magnets are switched to DC mode, which allows the currents to be set.

A procedure (left diagram in Fig. 1) was developed that uses the information broadcasted by the timing system to synchronize with the machine cycle and force the magnet power supplies to enter the DC mode after the beam acceleration is complete. Before the end of the cycle, orbit correction is disabled, magnet strengths are ramped down to the initial values and the function generators are rearmed. Each time the magnet controllers are switched to DC mode, the orbit correction procedure (right diagram Fig. 1) can take place. The correction step starts with the orbit measurement, which serves as input for the orbit correction algorithm that calculates the new steerer corrections via Eq. 3. Finally, a portion of the new corrections is applied to the steerer magnets. Cycle control and orbit correction (Figure 1) are both implemented in Sequencer [8], an EPICS (Experimental Physics and Industrial Control System) [9] module used to develop state machines in a C-like language. Calculation of the steerer strengths is written in C and takes advantage of GSL (Gnu Scientific Library) [10] to construct an orbit control matrix, perform SVD and solve the system of Eq. 3.

COSY beam position monitors, steerer controllers and the timing cards are connected to the control system network using 10 Megabit non switched Ethernet and can be controlled using custom SCSR (Single Command Single Response) protocol based on TCP and UDP. EPICS device support was implemented with StreamDevice [11]. During orbit measurement and control of the steerer magnets the computer running orbit correction algorithm has to communicate with a large number of devices in a short amount of time, which results in inconsistent reply times in a non switched network. Additional measures like on the fly generation of the orbit control matrix had to be taken to minimize the effect of frequent network timeouts on the orbit correction performance. A custom graphical user interface for CSS (Control System Studio) [12] was developed in Java to allow control over the orbit correction procedure and view the results.

## RESULTS

The slow orbit feedback system was tested in a three step process. In the first step after the software was finalized it was installed on the Control System Computers and in parallel to the regular setup of the accelerator the functionality was tested. Here especially the first time use of the EPICS IOC in parallel to the traditional control system and its connections to the different existing subsystem (Timing, BPM, Corrector Magnets) was setup and verified to work without any interference. Also the newly invented procedure of switching into DC mode was verified to work properly. As a second step a campaign using the stored COSY beam was executed to ensure that the new implementation of the already tested orbit correction based on measured ORMs works properly. In addition the use of model predicted values of the orbit response was implemented. To get a clear picture of the induced orbit changes and the operation of the correction this was tested with a regular COSY setting and the orbit of this setting served as reference orbit. Local three




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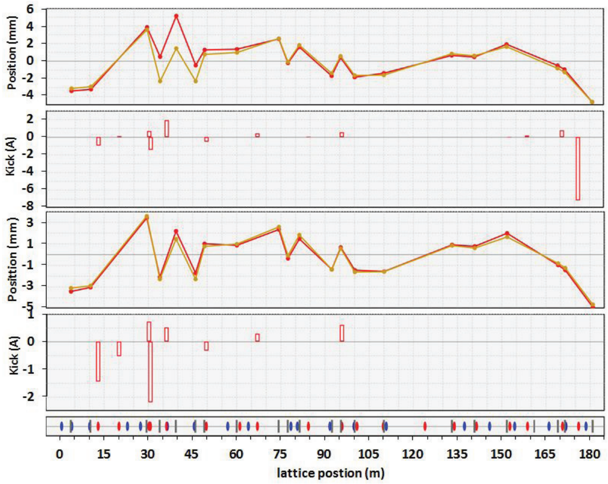


Figure 2: Detail of the graphical user interface, showing the present and the golden orbit and the set current of corrector magnets. In the upper panel a local three corrector orbit bump (red) was introduced with respect to the reference orbit (orange). The lower panel shows the orbit after correction, which is in good agreement with the reference orbit.

corrector orbit bumps were introduced to have dedicated deviation of the measured orbit to that reference orbit. The orbit correction system was then used to apply a correction to the corrector magnet and restore the reference orbit. This was verified to work properly for different locations of horizontal and vertical orbit bumps around the COSY ring. In Fig. 2 an example of such a procedure showing the reference golden orbit and the orbit with bump, and the recovery of the reference orbit after the correction is executed. Figure 3 shows an oscilloscope screenshot during the explained bump correction, where a clear change of the corrector magnet current for the vertical correctors SV20 and SV14 is visible. The improvement of the RMS orbit distortion with respect

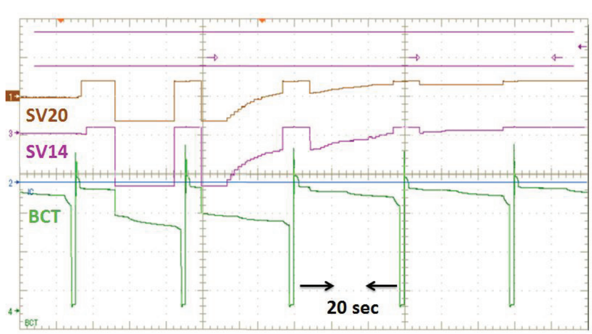


Figure 3: Exemplary oscilloscope screenshot during orbit correction. The green (lower) graph shows the beam current as function of time, indicating several machine cycles. In purple and brown the current through two vertical corrector magnets, namely SV20 and SV14 is displayed. Whereas the first cycle shows a regular ramp, during cycle number two the correction starts indicated by a step wise adjustment of the corrector current.

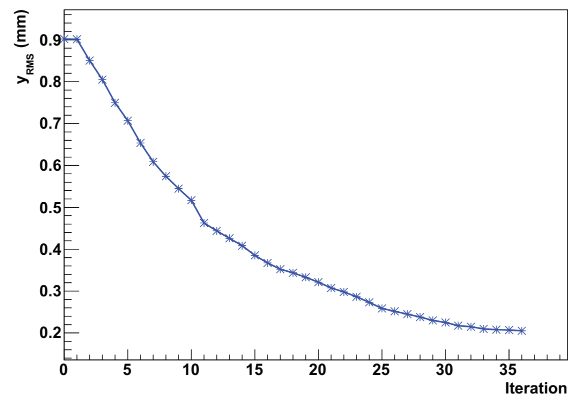


Figure 4: Correction of an artificially created local orbit bump. The rms of the vertical closed orbit distortion with respect to the initial orbit is displayed as function of the number of applied orbit corrections.

to the reference orbit is displayed in Fig. 4 as function of the number of applied orbit corrections.

In the next step the orbit feedback was activated. Here the orbit is repeatedly measured in certain time steps (here 4 s) during the full accelerator timing cycle (60 s) and after each measurement an adjustable fraction of the calculated correction is applied to the corrector magnets. A test of a correction of the existing orbit towards the zero orbit (all BPMs at zero) also was successful. Because of limited time this couldn't be tested in detail and will be done in a final commissioning run.

The archiving of data in the EPICS Archiver Appliance [13] was setup for continuous monitoring of the status of the orbit correction and its subsystems.

## PLANS FOR FUTURE

Before the slow orbit feedback is put into regular operation the complete system will undergo a final test during a commissioning run in May 2017. It will be verified that the correction will work for a selection of frequently used regular COSY setups. A long term test on the operation reliability of the system, which was not possible during the restricted time of the previous test periods, will be executed. The next step in enhancing the beam position accuracy towards the 100 µm goal is the upgrade of the BPM readout electronics system. The decision was made to use the commercially available Libera Hadron system. The hardware was delivered end of 2016 and the commissioning of the system is planned in July 2017.

In addition, the positioning of all main magnets in the COSY ring were reevaluated. The first geodetic measurement [14] showed deviations of the magnets for some more than 1 mm. The effect of this misalignment was calculated to cause 4.5 mm RMS of the beam position offset. Therefore an iterative process of measuring and correcting the positions of all magnets was initiated. The geodetic survey of the magnets is now in it's second iteration and is expected to be finished within this year.

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