ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPGW024

BEAM-BASED ALIGNMENT AT THE COOLER SYNCHROTRON COSY

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Abstract

There is a matter-antimatter asymmetry observed in the universe that cannot be explained by the Standard Model of particle physics. To resolve that problem additional CP violating phenomena are needed. A candidate for an additional CP violating phenomenon is a non-vanishing Electric Dipole Moment (EDM) of subatomic particles. Since permanent EDMs violate parity ant time reversal symmetries, they also violate CP symmetry if the CPT-theorem holds.

The Jülich Electric Dipole moment Investigation (JEDI) Collaboration works on a direct measurement of the Electric Dipole Moment (EDM) of protons and deuterons using a storage ring. Therefore an ongoing upgrade of the COoler SYnchrotron (COSY) is done in order to improve the precision of the beam position. One part of this upgrade is to determine the magnetic center of the quadrupoles with respect to the beam position monitors. This can be done with the so called beam-based alignment method. First results of the measurements at COSY will be discussed.

INTRODUCTION

There is an observable matter-antimatter asymmetry in the universe which can not be explained by the Standard Model of particle physics. In order to get an explanation for that additional CP violating effects are needed [1]. An additional CP violationg effect can originate from permanent Electric Dipole Moments (EDM) of subatomic particles. The EDM is violating parity and time reversal symmetry. Thus it also violates CP symmetry if the CPT-theorem holds. The predictions of EDMs of the Standard Model are orders of magnitudes too small to explain the dominance of matter in the universe. The discovery of a lager EDM would then hint towards physics beyond the Standard Model and yield a contribution towards an explanation for the dominance of matter.

The observation of EDMs of subatomic particles is possible by observing their interaction with electric fields. For neutral particles (e.g. the neutron [2]) this can be done in small volumes and no accelerator is needed, as they are not charged and thus not accelerated by the electric field. For charged particles it is more difficult, and as the Jülich Electric Dipole moment Investigation (JEDI) Collaboration wants to measure the EDM of the proton and the deuteron, there is the need for a storage ring. The storage ring has to be very precise [3] in order to reduce the systematic error to an acceptable level. In order to improve the precision of the Cooler Synchrotron (COSY) the beam-based alignment method is being used to align the magnetic centers of the quadrupoles and the beam position monitors. After a first test with only one quadrupole [4], now the measurement was performed for 12 out of 56 quadrupoles in COSY where the measurement was directly possible.

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Table 1: Explanation of the Parameters in Eq. (1)

Parameter	Meaning
Δx	Orbit change
s	Measurement position
s_0	Position of quadrupole
Δk	Change in quadrupole strength
$x(s_0)$	Position of the beam with respect to the magnetic center of the quadrupole
ℓ	Length of quadrupole
$B\rho$	Magnetic rigidity of the beam
k	Quadrupole strength
β	Beta function
ν	Betatron tune
ϕ	Betatron phase

THEORETICAL DESCRIPTION OF BEAM-BASED ALIGNMENT

In order to determine where the magnetic center of a quadrupole is, one can use the effect that if the beam is not centered inside the quadrupole, that there is a dipole component to the field which the beam sees. If one then varies the quadrupole strength one also varies the dipole component of the field, which the off center beam sees. Due to that, the orbit in the accelerator will change and one can observe that change. The change of the closed orbit depends on the offset of the beam inside the quadrupole where the strength is varied. The change of the orbit [5] can be described by

$$\Delta x(s) = \frac{\Delta k \cdot x(s_0)\ell}{B\rho} \frac{1}{1 - k\frac{\ell\beta(s_0)}{2B\rho\tan\pi\nu}} \times \frac{\sqrt{\beta(s)}\sqrt{\beta(s_0)}}{2\sin\pi\nu} \cos[\phi(s) - \phi(s_0) - \pi\nu], \quad (1)$$

where the parameters are explained in Table 1.

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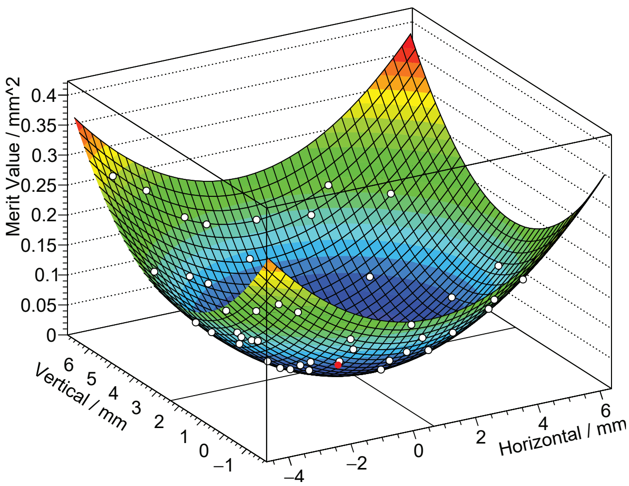

Figure 1: Example for one of the fits to determine the optimal position inside the quadrupole. On the x- and y-axis the beam position in horizontal and vertical direction is shown. On the z-axis the calculated merit function (eq. (2)), as explained in the previous section, is given. The white dots are the measured values (errors not shown here) and the colored plane is the fit to the data. The red dot is the minimum of the fit, i.e. the optimal position. The lines on the bottom of the plot are to help visualizing the optimal position.

From eq. (1) one can see that the orbit change Δx is proportional to the beam position inside the quadrupole $x(s_0)$. Unfortunately not all parameters of eq. (1) are perfectly known, thus the proportionality is very beneficial. This way one can use a simple merit function to extract the optimal position inside the quadrupole out of the measured data. The merit function that was used for this measurement is

$$f = \frac{1}{N_{\mathrm{BPM}}} \sum_{i=1}^{N_{\mathrm{BPM}}} \left(x_i(+\Delta k) - x_i(-\Delta k)\right)^2 . \qquad (2)$$

For that merit function one has to take two measurements for each beam position inside the quadrupole. One with slightly increased ($+\Delta k$) and once with slightly reduced ($-\Delta k$) quadrupole strength. The difference of the beam position x_i at the i-th beam position monitor is summed up in quadrature for all beam position monitors (see eq. (2)). By taking a closer look at the merit function one can see that it is proportional to the offset of the beam inside the quadrupole squared $f \propto (\Delta x)^2 \propto (x(s_0))^2$. This way one can do multiple measurements with different beam positions and determine the minimum of the merit function, which has the shape of a paraboloid. By finding the minimum, the optimal position for the beam inside the quadrupole can be determined.

EXPERIMENTAL TECHNIQUE AND RESULTS

For each of the twelve quadrupoles multiple measurements at different horizontal and vertical positions inside the quadrupole were performed. Each measurement consisted of 50 data points, where each point was measured in one cycle with both increased and reduced quadrupole strength. This was done in order to not get an additional systematic error due to slightly different injections between different cycles, as different injection points with a shift of a few tens of µm have been observed at COSY [6]. For each of the sets of 50 data points a fit was done and the optimal position was determined. One example for that can be seen in Fig. 1. There one can nicely see the expected behavior of a paraboloid shape as explained before.

All measurements for one quadrupole were then combined to a pair of values. This resulting optimal position inside all of the quadrupoles can be seen in Fig. 2. Some of the quadrupoles are close together and refer to the same beam position monitor. These quadrupoles close together are the pair QT17 and QT18 or QT21 and QT22. The determined optimal positions inside them are close together, as they are mechanically aligned with respect to each other with a precision of 0.2 mm [7].

With the determined offsets between the center of the quadrupoles and the beam position monitors one can now calibrate the position of beam position monitors, as they have no fiducial marks to which they can be aligned. With these results it was possible to calculate the offsets for six beam position monitors, which are now properly calibrated. All of the beam position monitors that could be calibrated are directly next to a quadrupole or in between two quadrupoles. For the beam position monitors in between two quadrupoles the result of both quadrupoles was combined to get the offset of the beam position monitor. Some of the optimal positions of the quadrupoles could not be used to calibrate a beam position monitor, because for those quadrupoles no beam position monitor was close by or there was no other quadrupole on the opposite side of the beam position monitor. The optimal positions which are not used right now will be used when more quadrupole measurements are available in the future.

In order to see that these determined offsets improve the orbit in the accelerator a short test was performed. For that test the orbit in the accelerator was corrected to be as close to zero a possible with the orbit correction software [8]. This correction was once done without the offsets of the beam position monitors applied and then again with the new offsets applied. The result of that test gave a better orbit RMS_y, which was reduced by 17% from 1.21 mm to 1.01 mm, while at the same time the strength of steerers needed to achieve the correction was also reduced by about 21%, which is a major improvement given the fact that only 12 out of 56 quadrupoles were used for this calibration. This means that one now has the zero position of the beam position monitors more precisely aligned with the optimal closed orbit, which is defined by the magnets.

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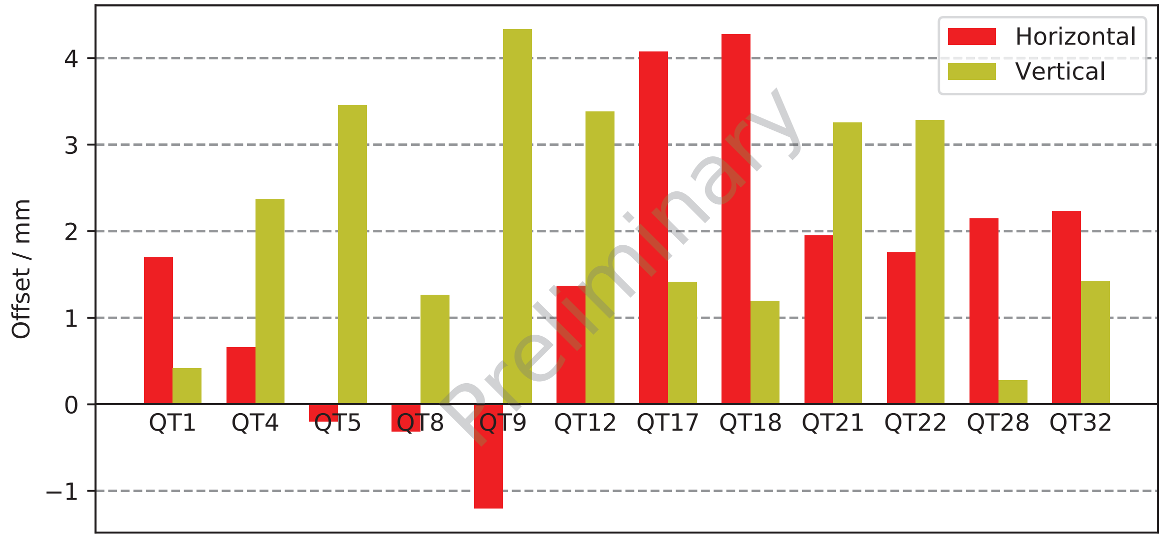

Figure 2: Preliminary results for all twelve quadrupoles. The optimal position of the beam inside quadrupole is displayed for the horizontal and vertical direction. The optimal position can be used to determine the offset of nearby beam position monitors. The errors on the optimal position are too small to be shown here.

CONCLUSION

The beam-based alignment measurement at COSY was a success and with that measurement six beam position monitors could be calibrated. Due to that, the precision of the orbit measurement improved. In addition less steerer strength was needed to obtain a better orbit RMS. This leads to an overall better orbit in the accelerator and in the end to a lower systematic error for the EDM measurement at COSY.

For the future a full measurement campaign for all 56 quadrupoles in the accelerator is planned, in order to be able to calibrate all beam position monitors and achieve an even better orbit in the machine.

ACKNOWLEDGEMENTS

The author wishes to thank the staff of COSY for providing excellent working conditions and for their support concerning the technical aspects of the experiment. He also thanks all involved members of the JEDI Collaboration and of the Institut für Kernphysik of Forschungszentrum Jülich. This work has been financially supported by Forschungszentrum Jülich GmbH and by an ERC Advanced-Grant (srEDM #694340) of the European Union.

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