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Analysis of closed orbit deviations for a first direct deuteron electric dipole moment measurement at the cooler synchrotron COSY

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Abstract. The Jülich Electric Dipole moment Investigations (JEDI) collaboration in Jülich is preparing a direct EDM measurement of protons and deuterons first at the storage ring COSY (COoler SYnchrotron) and later at a dedicated storage ring. Ensuring a precise measurement, various beam and spin manipulating effects have to be considered and investigated. A distortion of the closed orbit is one of the major sources for systematic uncertainties. Therefore misalignments of magnets and residual power supply oscillations are simulated using the MAD-X code in order to analyse their effect on the orbit. The underlying model for all simulations includes the dipoles, quadrupoles and sextupoles at COSY as well as the corrector magnets and BPMs (Beam Position Monitors). Since most sextupoles are only used during beam extraction, the sextupole strengths are set to zero resulting in a linear machine. The optics is adjusted in a way that the dispersion is zero in the straight sections. The closed orbit studies are performed for deuterons with a momentum of 970 MeV/c.

1. Introduction

The observed Matter-Antimatter asymmetry in the Universe cannot be explained by the Standard Model (SM) of Particle Physics. In order to resolve the matter dominance an additional $\mathcal{CP}$ violating phenomenon is needed. A candidate for physics beyond the SM is a non-vanishing Electric Dipole Moment (EDM) of subatomic particles. Since permanent EDMs violate parity and time reversal symmetries, they are also $\mathcal{CP}$ violating if the $\mathcal{CPT}$-theorem is assumed. Since the Standard Model (SM) predicitons for EDMs are many orders of magnitude too small to explain the dominance of matter, the discovery of larger nucleon EDMs would indicate physics beyond the SM and could give an explanation for the Matter-Antimatter asymmetry [1]. The interaction of a particles' spin with strong electric fields enables the measurement of an EDM. The underlying experiments need to be performed with high-precision storage rings and require an accurate measure and control of the spin and the beam. The JEDI collaboration therefore investigates spin and beam influencing effects in order to allow for EDM studies at COSY [2] [3].

2. Magnet misalignments

The magnet strengths and their positions mainly determine how the beam propagates through the ring. It is therefore important to investigate the effect of misaligned quadrupoles and dipoles in the model and to compare them to the actual setup of COSY [4]. Considering magnet misalignments for each dipole and quadrupole, six independent Gaussian distributed positioning errors (displacement along each axis, rotation around each axis) are generated according to

$$\Delta(x, y, s, \phi, \Theta, \Psi) = \mathrm{Gauss}(0, \sigma_{x,y,s,\phi,\Theta,\Psi}), \tag{1}$$

with $\frac{\sigma_x}{\mathrm{m}} = \frac{\sigma_y}{\mathrm{m}} = \frac{\sigma_s}{\mathrm{m}} = \frac{\sigma_\phi}{\mathrm{rad}} = \frac{\sigma_\Theta}{\mathrm{rad}} = \frac{\sigma_\Psi}{\mathrm{rad}}$, where $x, (y, s)$ describes the displacement along the x- (y-, s-) axes. Rotations around the axes are indicated respectively by ϕ, Θ and Ψ.

Including these magnet misalignments in the model, the closed orbit is simulated and the closed orbit RMS[1] is calculated in both transverse directions. Te reference particle is assumed to have a vanishing momentum deviation. All transfer matrices in MAD-X [5] are based on the optical functions given in [4]. The BPMs as well as the corrector magnets are assumed to be ideal in order to investigate only the effect of magnet misalignments. The results are considered before and after applying an orbit correction[2]. For each standard deviation 1000 random samples of magnet misalignments are used. Averaging over all 1000 sample values leads to the mean closed orbit RMS in horizontal and vertical direction. The simulation results for the accumulated effect of displacements and rotations of dipoles and quadrupoles are shown in figure 1 in both transverse directions including a linear fit to the data. The error bars indicate the standard errors of the mean values. Since the model is based on a linear machine the behaviour in both transverse directions is strictly linear. The results in both directions are not equal since the optical functions in horizontal and vertical direction differ from each other and the horizontal orbit response is also influenced by dispersion. The measured uncorrected closed orbit RMS at COSY in 2016 was of the order of a couple of millimeter, which corresponds to a simulated standard deviation of about 0.5 mm. Since the simulation results after the orbit correction do not include BPM resolution constraints and corrector magnet uncertainties, they cannot be directly compared to the measured corrected closed orbit at COSY. In order to perform a high precision experiment one aims to reach a closed orbit RMS of about 100 µm in the future by improving the magnet positioning [6].

2.1. Survey at COSY

The former results show that magnet misalignments are one of the main sources of closed orbit deviations at COSY. It is therefore necessary to determine the current positions of all dipoles and quadrupoles and to correct large displacements and rotations towards the target position. A corresponding survey was conducted in April 2016. The dipoles and quadrupoles at COSY are armed with reference marks. A laser-based position measurement can be carried out according to a fixed reference point. The positioning of these marks on the magnet is sketched in figure 2 [7].

Taking the first dipole in the left arc as the reference point, the relative vertical displacement of all other dipoles is measured. The same procedure is used for quadrupoles, taking the first quadrupole after the injection point as the reference element. Given these information a best-fit-plane was estimated to which all elements afterwards should be optimally positioned. The best-fit-plane is found by taking the vertical measurement results and fitting a plane to the values which minimizes the vertical deviations. It turned out that taking only the reference marks P2 and P3 of the dipoles into account leads to the most accurate result for the fitted plane. Ignoring some outliers of the measurement points further improves the result [7]. Finally,

[1] Root Mean Square
[2] Using Singular Value Decomposition (SVD) of the response matrix

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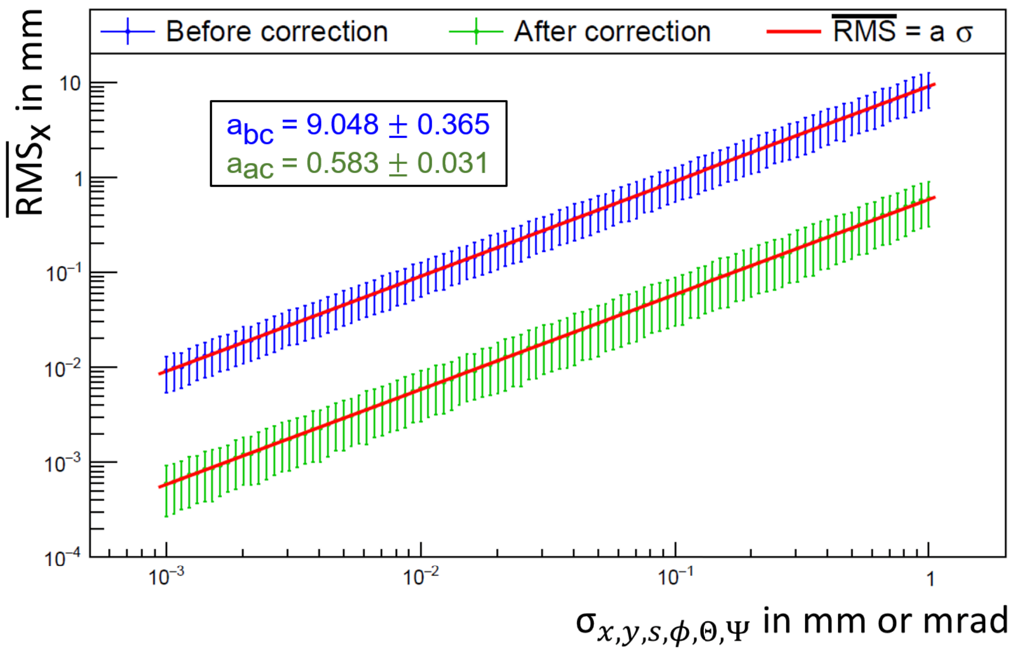

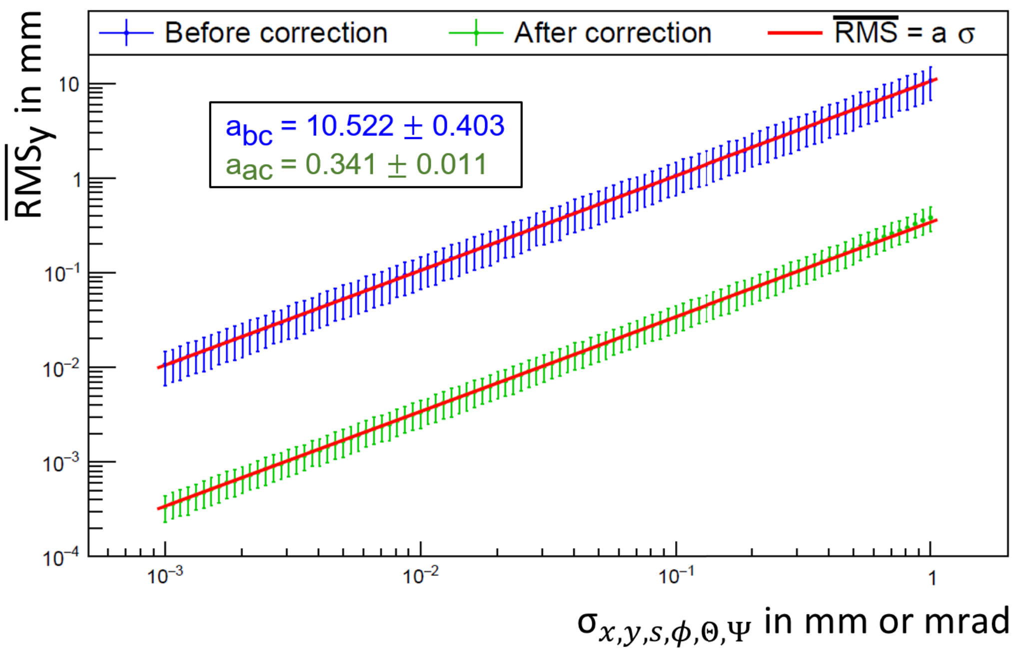

Figure 1. Mean closed orbit RMS in horizontal and transverse direction for simultaneous displacement and rotation of dipoles and quadrupoles. Blue markers: results before orbit correction. Green markers: results after the orbit correction. The values result from generating magnet misalignments using 1000 random seeds.

the deviations of all magnets from the achieved best-fit-plane were calculated in each direction using the several reference marks. Implementing the measured magnet misalignments into the

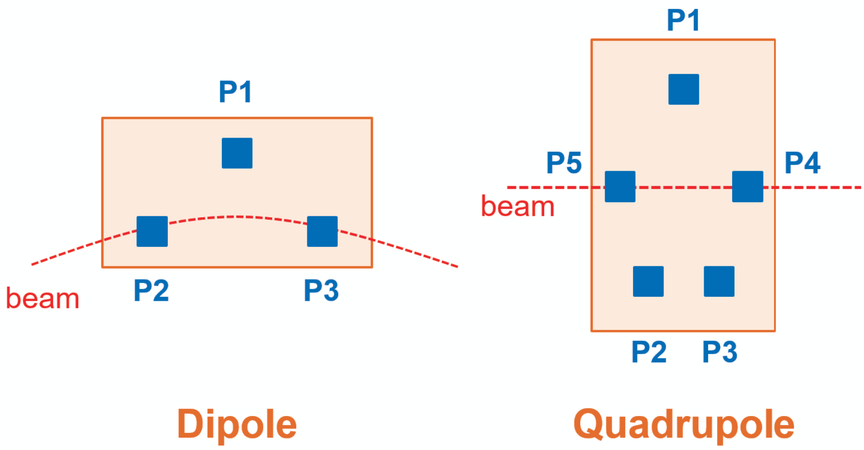

Figure 2. Topview on magnets: Reference marks on dipoles and quadrupoles. For dipoles the marks P2 and P3 are the closest to the beam path. In the case of a quadrupole, the marks P4 and P5 lie directly above the ideal beam trajectory through the magnet. [7]

COSY model leads to the uncorrected closed orbit shown in figure 3. The closed orbit RMS values are similar to the ones that are measured at COSY [8] which supports the assumption that magnet misalignments are the main source for closed orbit deviations. The comparison of the simulated corrected closed orbit and the measured one is not suitable since BPMs and correctors are assumed to be ideal in the simulation.

3. Power supply oscillations

One reason for field changes in the magnets are residual power supply oscillations which induce oscillating magnetic fields and cannot be controlled with the static orbit control system of COSY. In order to investigate the effect of residual power supply oscillations on the transverse closed orbit RMS, a sinusoidale oscillation with an amplitude of $\Delta I_{\mathrm{max}}/2$ is assumed, where ΔI_{max} indicates the peak-to-peak value resulting from the relative errors and the maximum provided current of the power supplies (figure 4). In table 1 the current uncertainties as well as the maximum possible current values for each type of magnet at COSY are summarized [9]. Independently of the magnet type, its strength depends linearly on the current. Thus one can easily deduce the oscillation of the magnet strength given its variation of the current [10]. For each power supply an amplitude of the sine wave is randomly generated using a Gaussian distribution with a standard deviation of $\Delta I_{\mathrm{max}}/2$. The resulting value for the change in current is then given by

$$\Delta I = \mathrm{Gauss}\left(0, \frac{\Delta I_{\mathrm{max}}}{2}\right). \tag{2}$$

Incorporating the generated field variations in the model and calculcating the closed orbit leads to a snapshot of the dynamic scenario. By creating various of these snapshots one can investigate the average influence of power supply oscillations on the transverse closed orbit with respect to a given reference orbit. In the simulaton 1000 snapshots, i.e. 1000 closed orbit calculations, each for a different set of current errors, are generated. For the reference orbit a fixed set of misaligned dipoles and quadrupoles was chosen. The method is sketched in figure 5.

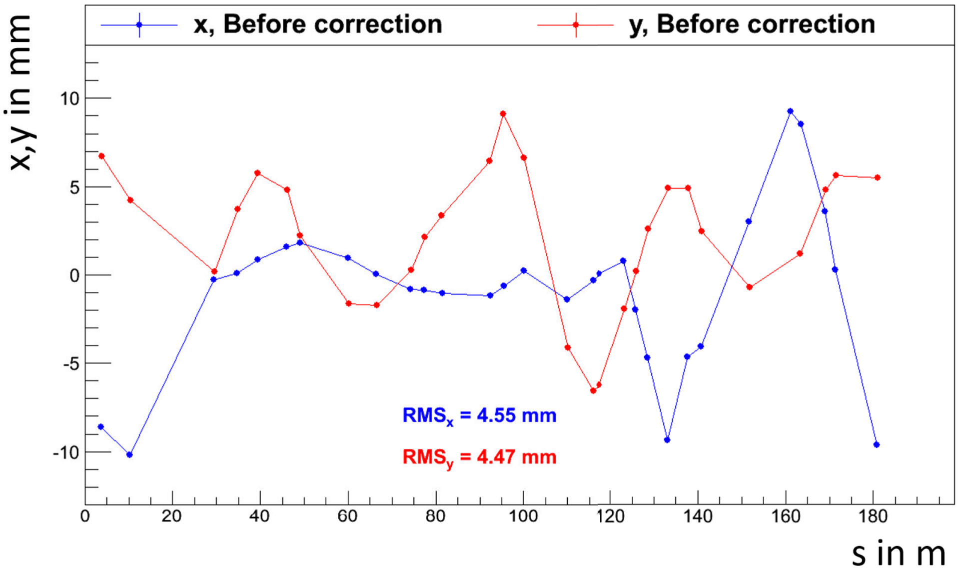

Figure 3. Simulated uncorrected closed orbit resulting from magnet misalignments taken from the survey data. The markers show the simulated BPM readings. The closed orbit RMS in the uncorrected case is similar to measured RMS values at COSY. Also the whole pathway of the uncorrected closed orbits show similarities to the measured orbits.

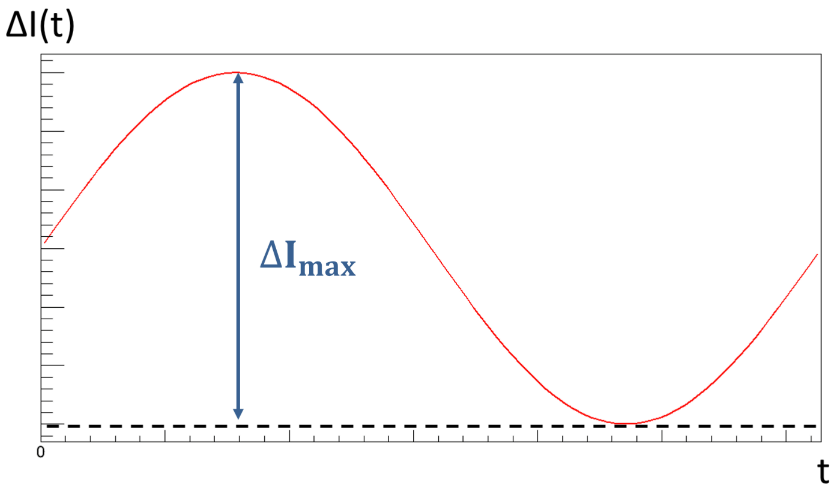

Figure 4. Sketch of sinusoidal residual power supply oscillation. The typical frequency of the power supply oscillation is approximately 600 Hz.

The deviations from the reference orbit at each BPM are collected in a histogram for all 1000 simulations and a Gaussian fit is performed to the data of each BPM. The width of the fit indicates the influence of the field oscillation at this specific BPM. The average width over all

Table 1. Relative error and maximum current of COSY magnets.

Relative error of the current of COSY magnets			
Magnet	σ [ppm]	I_{max} [A]	ΔI_{max} [A]
Dipole	20	5000	100
Quadrupole	20	550	11
Sextupole	500	275	137.5
Corrector	100	30	3

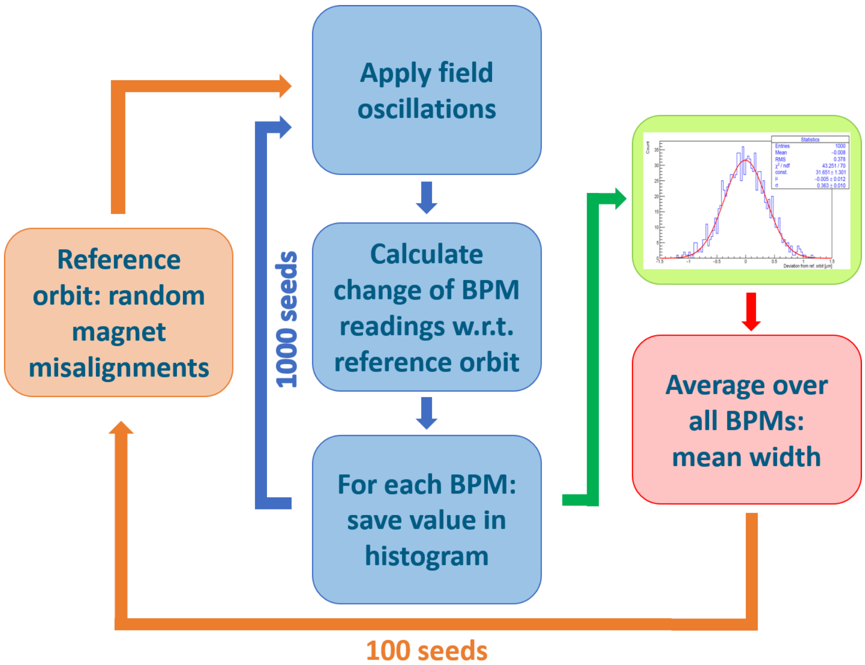

Figure 5. Simulation method of power supply oscillation influence on the transverse closed orbit of COSY.

BPMs indicates the influence on the closed orbit RMS in x- (y-) direction with respect to the given reference orbit. The procedure is repeated for 100 different reference orbits. Averaging over all reference orbits describes the global influence of field changes caused by residual power supply oscillations. The results for each magnet type are summarized in table 2. None of the RMS changes is of a larger order of magnitude than 10 µm.

4. Conclusion

The simulations show that the closed orbit at COSY is influenced much more by magnet displacements and rotations than by residual power supply oscillations. The effects of misaligend magnets dominate the effect of power supply oscillations by many orders of magnitude. Implementing the measured magnet deviations form the target positions into the simulation

Table 2. Influence of residual power supply oscillations of the COSY magnets on the transverse closed orbit RMS.

Closed orbit changes due to power supply oscillations		
Magnet	$\Delta\overline{\mathrm{RMS}}_x$	$\Delta\overline{\mathrm{RMS}}_y$
Dipole	(27.69 ± 0.24) µm	(9.00 ± 0.10) nm
Quadrupole	(1.11 ± 0.01) µm	(0.70 ± 0.01) µm
Sextupole	(48.70 ± 0.90) nm	(49.90 ± 0.60) nm
Corrector	(34.43 ± 0.30) µm	(28.07 ± 0.22) µm

model of COSY leads to similar closed orbit RMS values than the measured ones. In a next step also sextupole strengths are included in the model in order to provide long spin coherence time [11] and furthermore BPM and corrector magnet constraints are implemented. Regarding the future EDM experiment at COSY, the residual power supply oscillations play a minor role when trying to improve the quality of the closed orbit to reach a transverse RMS of about 100 µm [6]. Currently, the COSY magnets are realigned to their target positions with an accuracy of 0.2 mm [7] in order to reduce the closed orbit RMS.

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