ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRO056

ESTIMATION OF SYSTEMATIC ERRORS FOR DEUTERON ELECTRIC DIPOLE MOMENT (EDM) SEARCH AT A STORAGE RING

S. Chekmenev for the JEDI collaboration, III. Physikalisches Institut, RWTH Aachen, 52056 Aachen, Germany

Abstract

An experimental method which is aimed to find a permanent EDM of a charged particle was proposed by JEDI (Juelich Electric Dipole moment Investigations) collaboration in 2012 [1]. EDMs can be observed by their small influence on spin motion. The only possible way to perform a direct measurement is to use a storage ring. For this purpose it was decided to carry out the first precursor experiment at the Cooler Synchrotron (COSY). Since the EDM of a particle violates CP invariance and is expected to be tiny, treatment of all various sources of systematic errors should be done with a great level of precision. One should clearly understand how misalignments of the magnets affect the beam and the spin motion. In reality, one of the methods to investigate spin behavior in the presence of misalignments in a storage ring is to mimic their influence on the beam parameters using small orbit kicks with different amplitudes. In this talk the first simulations of orbit excitations will be discussed. The corresponding spin tune shifts will be considered. The influence of the distorted orbit on the polarization build-up caused by the EDM will be examined.

INTRODUCTION TO THE EDM STORAGE RING EXPERIMENT

The main goal of a search for an Electric Dipole Moment (EDM) at the all-magnetic ring COSY is to observe a build-up of a polarization in a particular plane caused by the presence of an EDM. The non-vanishing EDM leads to spin rotations in the electric field according to Frenkel-Thomas-Bargmann-Michel-Telegdi equation

$$\begin{aligned}\frac{d\vec{S}}{dt} &= \vec{\Omega}\times\vec{S},\\ \vec{\Omega} &= -\frac{e}{m}\Big\{\underbrace{G\vec{B} + \Big(\frac{1}{\beta^2} - G - 1\Big)\vec{\beta}\times\vec{E} +}_{\text{MDM}}\\ &+\underbrace{\eta\Big(\vec{E}+\vec{\beta}\times\vec{B}\Big)}_{\text{EDM}}\Big\},\end{aligned} \tag{1}$$

where underbraced the magnetic dipole moment (MDM) and EDM contributions to the spin precession, and

$$\eta = d\frac{m}{e}$$

is the EDM in units of the nuclear magneton. The default prediction from CP-violation models is $\eta \sim 10^{-10}$. [2] In a pure magnetic ring, where $\vec{E} = 0$, the EDM interacts with the motional electric field, which tilts the stable spin axis,

$$\begin{aligned}\vec{\Omega} &= -\frac{e}{m}\Big\{G\vec{B} + \eta\vec{\beta}\times\vec{B}\Big\}\\ &= \Omega_R\frac{G\gamma}{\cos\xi}\cos\xi\vec{e_y} + \sin\xi\vec{e_x},\end{aligned} \tag{2}$$

and modifies the spin tune,

$$\nu_s = \frac{G\gamma}{\cos\xi}, \quad \tan\xi = \eta. \tag{3}$$

The spin tune ν_s is defined as the number of spin revolutions relative to the momentum vector per turn around the spin closed orbit. One can use a so-called resonant Wien filter in this case to be able to observe a growth of the EDM signal with time (see [3] for details). The basic property of such a device is that it impacts zero Lorentz force on the beam,

$$\vec{E} + \vec{\beta}\times\vec{B} = 0. \tag{4}$$

This immediately indicates the EDM transparency of the Wien filter. However, it produces a kick to the phase of the spin precession around the vertical axis, which changes it from the idle one to RF-modulated one. As a result, there is an accumulation of the EDM effect throughout the whole ring [3]

IMPERFECTIONS OF THE RING

As one knows for sure, there is no perfect machine in real life. In the all-magnetic ring the interaction of an MDM with imperfection magnetic fields mimic the interaction of an EDM with the motional electric field. Therefore, one has to take into account the generated effect on the beam and spin motion due to the presence of those fields. Primarily, misaligned magnets produce the imperfections which will be considered in this paper. Obviously, this is one of the main sources of systematic errors in the experiment.

It is very convenient to study the motion of the beam and the spin in a non-perfect accelerator using spin tune measuments. In an ideal magnetic ring in the absence of an EDM the spin tune is given by the product of the relativistic γ-factor and the anomalous magnetic moment G, $\nu_s = G\gamma$. Misalignments and other perturbations lead to modification of the spin tune which make it an excellent tool to investigate systematic effects. A tremendous precision of 10^{-10} for the average spin tune in a single 100s cycle was achieved during the latest runs at COSY. This corresponds to the relative precision of $10^{-10}/0.16 = 6\cdot 10^{-10}$. There is a plan to see deeply into misalignment issue at the time of the upcoming run. It is suggested to mimic the influence of imperfections on the beam parameters using small excitations of the orbit with steerers placed inside the ring. The simulation for this was process was done and will be discussed below.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2014). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRO056

SPIN TUNE SIMULATIONS IN IMPERFECTION FIELDS

A powerful spin-tracking simulation program is an essential point in the preparation for the experiment. Further studies were performed in MODE (Matrix Integration of Ordinary Differential Equations) program [4]. MODE provides high-order nonlinear matrix maps building for spin and beam dynamics simulations.

MODE Benchmarking

Before the actual simulation of orbit excitations MODE was tested for its correctness. The idea was to benchmark the tracking results with the experimental data for the extraction process which took place during the last run. The decision to do that was initiated not only by the fact that MODE was needed to be tested, but, in addition, by the demand of explanation of the spin tune rise during the horizontal extraction. The extraction of the beam was made by using two horizontal steerers with linearly increasing magnetic fields. The simulation result is presented in Figure 1.

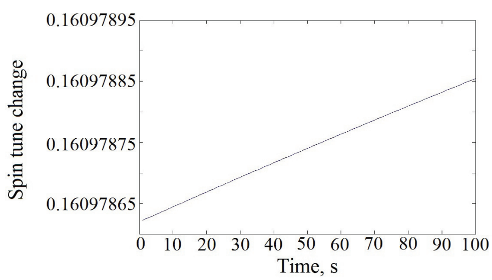

Figure 1: The simulation of the spin tune change during the horizontal extraction at COSY

It was obesrved experimentally that during the extraction the absolute spin tune change was approximately $\delta\nu_s = 2.53 \cdot 10^{-7}$. As one can see in the picture, the spin tune increases slightly slower in the simulation ($\delta\nu_s = 2.25 \cdot 10^{-7}$), which testifies for the fact that not all of the existent fields were properly described or took into account. The later work is needed to get the full matching between the experiment and the simulation. The simple explanation for the spin tune change may be presented in the following manner:

$$\phi_{s_{tot}} = \underbrace{(\nu_s + 1)\phi_{steerer}}_{\text{inside a steerer}} + \underbrace{\nu_s \phi_{ring}}_{\text{for the rest of the ring}} , \qquad (5)$$

where $\phi_{s_{tot}}$ is a total spin rotation angle per one revolution. If one devides this value by 2π, it gives a spin tune value. Since the magnetic field of the steerers rises linearly with time, therefore the spin tune also increases linearly.

Orbit Excitations and Corresponding Spin Tune Changes

The idea to study the effects on the beam parameters, caused by misalignments in the ring, using two steerers which excites an orbit is simple and easy to realize. It was proposed to use two steerers (a horizontal and a vertical one) placed separately at two straight sections at COSY. The steerers then kick the beam in the vertical and in the horizontal direction imitating a presence of the imperfection field. The corresponding spin tune shift is measuared aftewards. In the simulation the initial beam position lay exactly on the reference orbit, all other magnets were not misaligned. Hence, two excitation steerers created new closed orbits for each steerer field setting (Figure 2).

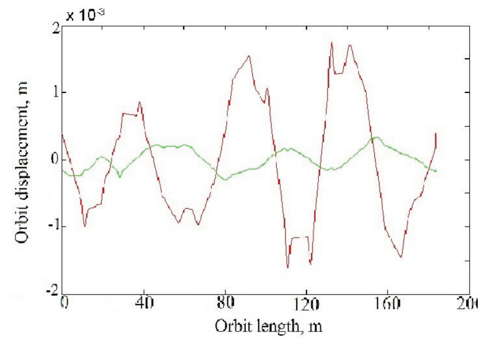

Figure 2: The closed orbits in horizontal (green) and vertical planes. The steerer kick was of the order of 10^{-4} radians

The values for the magnetic field of the steering dipoles were normally distributed with a particular sigma. Two hundred different "cycles" were done and the spin tune was calculated for each of them. Each dot represents a spin tune value for each "cycle" respectively (Figure 3).

One can see that the steerer kicks of the order of 10^{-4} radians correspond to the relative spin tune shifts of the order of 10^{-3}. As the steerer strength drops, the orbit becomes closer to the reference one, and consequently the order of the spin tune spread decreases. It depends linearly on the kicks. This dependence will be tested experimentally in the upcoming run in September this year at COSY.

ESTIMATION OF SYSTEMATIC ERRORS WITH A RESONANT WIEN FILTER

An EDM of a particle is very sensitive to all kinds of imperfections and to misalignments in particular. The use of the resonant Wien filter needs, apart from other issues, a fantastic orbit correction. Below simulations with and without misalignments included are presented. Two cases was compared in order to get a first result on the systematic limit for existent COSY ring (Figure 4 and Figure 5).

The electric field of the Wien filter was set to 10 kV/cm. The magnetic field was calculated by formula 4. Longitudinally polarized deuteron located right on the closed ordit was tracked through the ring 10^4 times. Build-up of a vertical polarization was observed. However,there are two different reasons for the rise of a polarization. In the first case (Figure 4) the perfect reference orbit was used and the build-up relates to the interaction of the EDM with the motional electric field in the ring. The EDM was equal to $2.63 \cdot 10^-21 e \cdot$ cm.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2014). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRO056

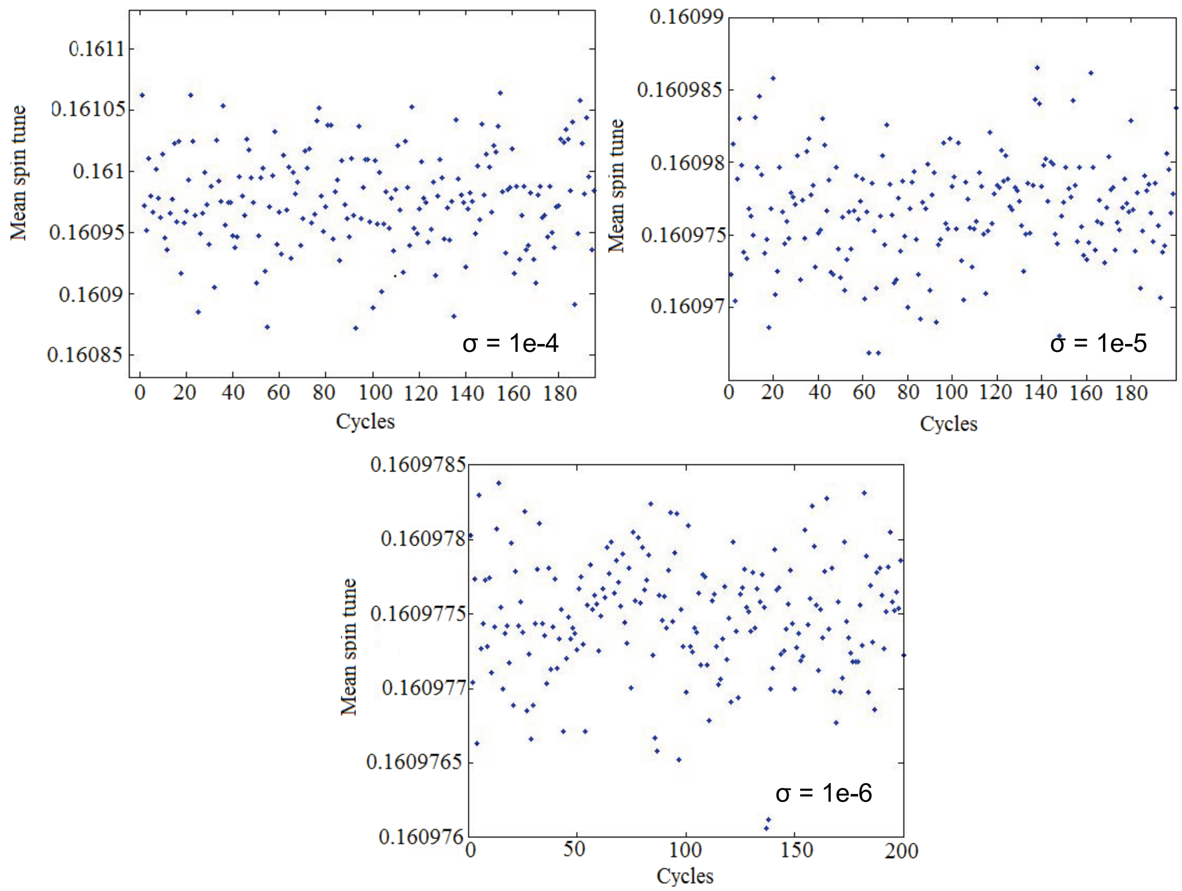

Figure 3: Mean spin tune values for different "cycles". Each "cycle" has its own magnetic field strength of the steerer. Different steerer strengths were normally distributed for different 'cycles" with a particular sigma.

In the second case (Figure 5) the polarization increased because of the interaction of the MDM with imperfection fields inside the ring.

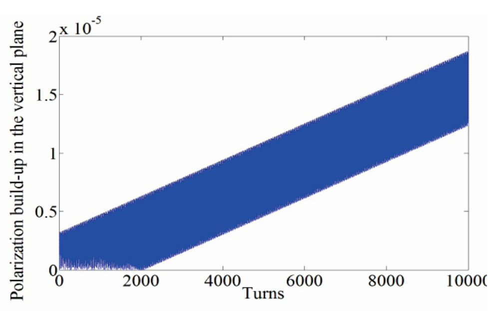

Figure 4: The polarization build-up due to EDM interaction with the motional electric field in the whole ring with Wien filter on. $\eta = 10^{-6}$, which corresponds to EDM is equal to $2.63 \cdot 10^{-21} e \cdot \mathrm{cm}$.

The present misalignments at COSY are of the order of 10^{-4} meters (or radians for rotations). As clearly seen in Figure 5, the polarization increases with the step of $7 \cdot 10^{-7}$

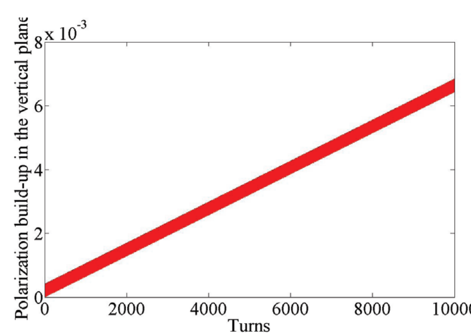

Figure 5: The polarization build-up due to interaction of MDM with imperfection fields of misaligned magnets with Wien filter on

per turn in the absence of EDM with misalignments at this order. The slope of a polarization rise due to the EDM in the absence of imperfections is equal to $1.6 \cdot 10^{-9}$ per turn. So one can say, that with the existent misalignments the systematic limit on the EDM for COSY ring is of the order of $10^{-19} e \cdot \mathrm{cm}$.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2014). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPRO056

CONCLUSION

The newest spin-tracking program MODE was tested in the simulation of the extraction process at COSY. The spin tune increases in the simulation with almost the same rate as in the experiment, which proves the correctness of algorithms used in the program. The orbit excitation simulation was done. It's possible to mimic the presence of the imperfection fields effect on the beam parameters with two steerer approach. The extraordinary sensitive tool, as the spin tune is, allows to measure the impact of tiny misalignmetns on the spin motion. The simulation shows the linear dependence of the spin tune on the steerer strength, and hence, on the orbit size. This approach will be tested in the upcoming run in September at COSY. Wien filter was implemented in MODE. The systematic effects due to imperfections in the ring were considered. Two types of tracking were performed for that reason, one with an EDM and a perfect orbit and another without one for the distorted case. The build-ups of polarization per turn were calculated for both situations and later compared in order to get the systematic limit on the current COSY configuration. The limit is of the order of $10^{-19} e \cdot \mathrm{cm}$. This value will be improved by further implementation of a new orbit correction system among other significant changes for the precursor experiment on the search for an Electric Dipole Moment of a charged hadron.

REFERENCES

[1] A. Lehrach, F. Rathmann, J. Pretz et al., "Search for Permanent Electric Dipole Moments at COSY. Step 1: Spin coherence and systematic error studies", 2012.

[2] A. Lehrach, J. Pretz, F. Rathmann et al., "Search for Permanent Electric Dipole Moments at COSY. Step 1: Spin coherence and systematic error studies", 2014.

[3] K. Nikolaev, "Duality of the MDM-transparent RF-E Flipper to the EDM transparent RF Wien-Filter at all Magnetic Storage Rings", 2013.

[4] A. Ivanov, "Matrix Integration of ODEs for Spin-orbit Dynamics Simulation", these proceedings.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2014). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.