DETERMINATION OF THE INVARIANT SPIN AXIS IN A COSY MODEL USING BMAD

M. Vitz*[1], A. Lehrach[1], Institut für Kernphysik 4, Forschungszentrum Jülich, 52425 Jülich, Germany
J. Pretz[1], Institut für Kernphysik 2, Forschungszentrum Jülich, 52425 Jülich, Germany
[1] also at III. Physikalisches Institut B, RWTH Aachen University, 52056 Aachen, Germany
on behalf of the JEDI Collaboration

Abstract

The matter-antimatter asymmetry might be understood by investigating the EDM (Electric Dipole Moment) of elementary particles. A permanent EDM of a subatomic particle violates time reversal and parity symmetry at the same time and would be, with the currently achievable experimental accuracy, an indication for further CP violation than established in the SM (Standard Model of Particle Physics). The JEDI-Collaboration (Jülich Electric Dipole moment Investigations) in Jülich has performed a direct EDM measurement for deuterons with the so-called precursor experiments at the storage ring COSY (COoler SYnchrotron) by measuring the orientation of the ISA (Invariant Spin Axis). In order to interpret the measured data and to disentangle a potential EDM signal from systematic effects, spin tracking simulations in an accurate simulation model of COSY are needed. Therefore a model of COSY was implemented using the software library Bmad. Systematic effects were considered by including element misalignments, effective dipole shortening, longitudinal fields and steerer kicks. These effects rotate the ISA in addition to the EDM and have to be analyzed and understood. The most recent spin tracking results as well as the methods to find the ISA are presented in this paper.

INTRODUCTION

In order to explain the matter-antimatter asymmetry in the Universe, CP-violating processes beyond those already known are needed [1]. A permanent non-vanishing EDM of a subatomic particle is a candidate for such a process, since it is a source of P and T violation leading to CP violation, assuming the CPT-theorem holds. An EDM is by far smaller than MDM (Magnetic Dipole Moment), but also predicted by the SM. As there is no direct measurement of the proton or deuteron EDM available so far, the JEDI collaboration has performed a first direct measurement of the deuteron EDM at the COSY accelerator facility in Jülich. Therefore the so-called precursor experiments were carried out in November 2018 and March 2021. A storage ring allows a direct measurement of an EDM, as the interaction of particle's spin with electromagnetic field results in spin rotations defined by EDM and MDM contribution [2, 3]. This paper describes the methodology used to determine the EDM signal and compares the experimental results with the simulation results. This is necessary in order to separate systematic effects caused by misaligned elements, steerer contributions, unknown longitudinal fields, etc., from a potential EDM signal [4]. The software tool used to study and benchmark the deuteron EDM effect in a simulation is the Fortran based library Bmad [5].

METHODOLOGY

The storage ring COSY located at Forschungszentrum Jülich is an ideal starting point for a first EDM measurement of charged particles as it provides phase-space cooled polarized and unpolarized deuteron and proton beams up to a momentum of 3.70 GeV/c. The central idea of the experiment, performed at a momentum of 0.97 GeV/c, is to measure the impact of the EDM on the beam polarization vector. For this purpose, a vertically polarized deuteron beam is injected into the ring, accelerated, bunched and cooled. The beam polarization is measured with a polarimeter by scattering a fraction of the particles on a carbon target. The asymmetry in the scattering rate indicates the polarization orientation [6]. A solenoid is used to rotate the polarization into the radial plane (= accelerator plane), where the polarization vector starts to rotate around the so-called ISA according to the Thomas-BMT equation [2]. In an ideal accelerator without an EDM and no systematic effects, the ISA would be parallel to the vertical magnetic dipole fields around the whole ring. However, the existence of an EDM of magnitude η tilts the ISA in radial direction by an angle $\phi_{\text{EDM}} = \arctan(\eta\beta/2G)$ as described by Eq. (1) and shown in Fig. 1.

$$\vec{n}_{\text{ISA}} = \begin{pmatrix} \sin\phi_{\text{EDM}} \\ \cos\phi_{\text{EDM}} \\ 0 \end{pmatrix} \approx \begin{pmatrix} \phi_{\text{EDM}} \\ 1 \\ 0 \end{pmatrix}. \tag{1}$$

Unfortunately ring systematics ($\phi_{\text{Ring}}, \xi_{\text{Ring}}$) like misaligned magnets, etc. tilt the ISA in addition to the EDM. A solenoid can be used to compensate the long. tilt ξ_{Ring} by an angle ξ_{Sol}. This is indicated in Eq. (2).

$$\vec{n}_{\text{ISA}} \approx \begin{pmatrix} \phi_{\text{EDM}} + \phi_{\text{Ring}} \\ 1 \\ \xi_{\text{Sol}} + \xi_{\text{Ring}} \end{pmatrix}. \tag{2}$$

As an experiment is not capable to measure the beam polarization vector each turn with sufficient statistical accuracy, another way of determining the ISA was identified. The so-called RF (Radio-Frequency) Wien filter, a RF device with a radial electric E_x^{WF} and vertical magnetic field B_y^{WF} was implemented into COSY. While the orbit in the center of this device is not perturbated, as the fields are set up so that

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* m.vitz@fz-juelich.de

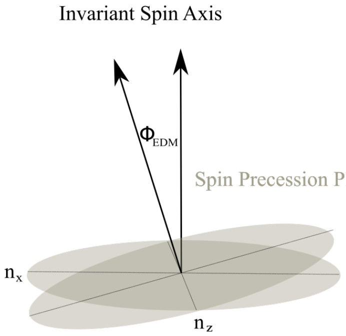

Figure 1: A permanent EDM of magnitude η tilts the ISA in radial direction n_x by an angle ϕ_{EDM}. The longitudinal direction n_z is not affected by a permanent EDM. Here n_z points in the moving direction of the particle beam, while n_x is perpendicular to n_z and shows into the accelerator plane.

the Lorentz force is zero, the particles receive a spin kick in the same direction each turn as the Wien filter is changing its fields on one of the harmonics k of the spin precession frequency ν_s. This way, the EDM signal can accumulate over time, resulting in a build-up of vertical polarization P_y if the Wien filter runs on resonance [7, 8]. Equation (3) and Eq. (4) are showing the adjustments of the Wien filter fields needed, to achieve this build-up.

$$E_x^{\mathrm{WF}} = E_0 \cos(2\pi f_{\mathrm{COSY}} |k + \nu_s| + \phi_{rel}) \tag{3}$$

$$B_y^{\mathrm{WF}} = B_0 \cos(2\pi f_{\mathrm{COSY}} |k + \nu_s| + \phi_{rel}). \tag{4}$$

The build-up $\epsilon \propto \frac{d}{dt} P_y(t)$ depends on the orientation of ISA $\vec{n}_{\mathrm{ISA}}$ to Wien filter fields $\vec{n}_{\mathrm{WF}}$ and the compensation of long. fields via solenoidal fields. To compensate the EDM signal and radial systematics ϕ_{Ring} the Wien filter is rotated by an angle ϕ_{WF} around beam. This is described by Eq. (5).

$$\begin{aligned}\epsilon^2 \propto |\vec{n}_{\mathrm{WF}} \times \vec{n}_{\mathrm{ISA}}|^2 &= \left| \begin{pmatrix} \phi_{\mathrm{WF}} \\ 1 \\ 0 \end{pmatrix} \times \begin{pmatrix} \phi_{\mathrm{EDM}} + \phi_{\mathrm{Ring}} \\ 1 \\ \xi_{\mathrm{Sol}} + \xi_{\mathrm{Ring}} \end{pmatrix} \right|^2 \\ &= ((\phi_{\mathrm{EDM}} + \phi_{\mathrm{Ring}}) - \phi_{\mathrm{WF}})^2 + (\xi_{\mathrm{Sol}} + \xi_{\mathrm{Ring}})^2.\end{aligned} \tag{5}$$

By plotting the build-up ϵ in dependency of ϕ_{WF} and ξ_{Sol} one receives an EDM resonance map. Its minimum indicates the point where all systematic effects in the ring as well as a potential EDM signal are compensated by the solenoid and the Wien filter. In addition, it is also possible to determine the long. ISA by observing the spin tune changes $\Delta\nu_s$ in dependency of the strength B_{Sol} of the solenoid [9]. This way one can determine the so-called solenoid calibration factor k_{Sol}, giving the relation between the solenoid field B_{Sol} and the spin kick $\xi_{\mathrm{Sol}} = k_{\mathrm{Sol}} \cdot B_{\mathrm{Sol}}$, as well as the projection of the long. ISA c_{Sol}. This is sketched by Eq. 6. It has to be mentioned that c_{Sol} is different from $\xi_{\mathrm{Sol}} + \xi_{\mathrm{Ring}}$. This will be shown and discussed later.

$$\Delta\nu_s = -\frac{1}{\pi}\left(\cot(\pi\nu_s)\left(\cos\frac{kB}{2} - 1\right)\right) - c \sin\frac{kB}{2}. \tag{6}$$

Both methods have been used in an experiment and in the simulation to determine the ISA for a lattice containing all known systematic effects.

RESULTS OF THE SIMULATION

EDM Resonance Map

A Bmad model of COSY was created according to the parameters given in Table 1.

Table 1: Relevant parameters for the deuteron EDM experiment at COSY.

Quantity	**Unit**	**Size**
Momentum	p	0.970 GeV/c
Velocity	β	0.459
Lorentz Factor	γ	1.126
Gyromagnetic Anomaly	G	-0.143
Rev. Frequency	f_{COSY}	752 kHz
Spin Prec. Frequency	$f_{\mathrm{COSY}} \cdot \nu_s$	121 kHz
Wien Filter Frequency	f_{WF}	873 kHz

To simulate the experiment used to determine the orientation of the ISA all known magnet strengths, misalignments, multipol fields and other systematic effects were included in the model. Using the resonant Wien filter method describe above, the point of no build-up of vertical polarization was identified. The result is displayed in Fig. 2 and compared to the experimental results in Table 2.

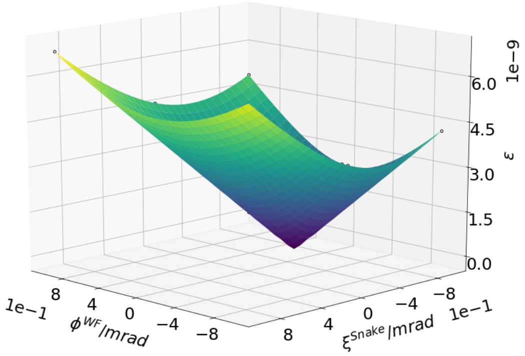

Figure 2: Simulated EDM resonance map including all known systematic effects and assuming no EDM.

Table 2: Results of the experiment compared with the corresponding simulation results.

Method	ϕ_{WF}	ξ_{Sol}
Experiment [10]	−2.91(8) mrad	−5.22(7) mrad
Simulation	−0.1119(3) mrad	−0.3697(3) mrad

Even though all known parameters and systematic effects have been included the results of experiment and simulation differ by one order of magnitude. So far it is unclear where this difference exactly comes from. One reason could be the inaccurate model, as it does not directly reflect the orbit and tune, even though all parameters and systematic effects are included. Another reason could be the need of correction factors as Eq. (5) and Eq. (6) are only valid for the beam passing through the devices without any angle. This will be discussed in the next section.

Solenoid Calibration and Correction Factors

As explained earlier the spin tune changes due to the solenoidal strength can be used to determine the long. ISA $n_{\mathrm{Sol},z}$ at the position of the solenoid. This method is shown in Fig 3.

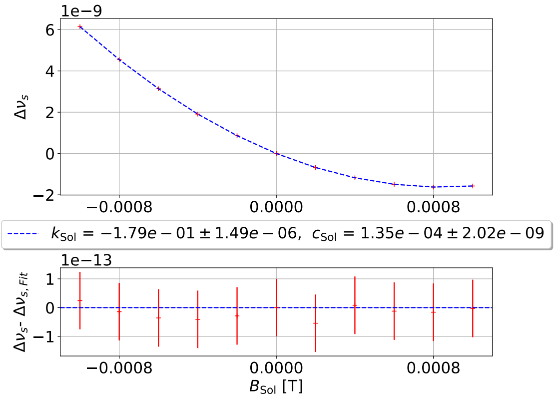

Figure 3: Calibration of the 2 MeV Solenoid for a lattice with all known systematic effects included.

For an ideal lattice, the fit parameter c_{Sol} coincides with the long. ISA at the position of the solenoid $n_{\mathrm{Sol},z}$. In case the lattice is distorted, a correction to the projection has to be applied. It can be shown that this correction is dominated by the vertical momentum when passing the solenoid. This is shown in Fig 4. There is evidence that a similar correction has to be applied to the EDM resonance map data. This is currently under investigation.

CONCLUSION

In this paper it was shown how the EDM and ring imperfections affects the ISA of a polarized particle beam. A measurement technique was introduced which uses a so-called RF Wien filter to accumulate an EDM signal over time to measure a build-up of vertical polarization. A solenoid was used to compensate the long. tilt of the ISA due to ring imperfection. This way an EDM resonance map can be created. Measured and simulated data have been compared and show a difference of one order of magnitude. There is evidence that improvements of the model, as well as identifying correction factor when passing through the Wien filter and the solenoid off axis will lead to a much better agreement between experimental results and simulated results. These objectives will be addressed in an upcoming beam time within the next months.

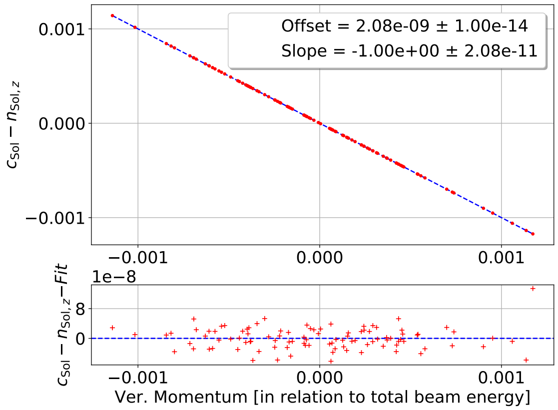

Figure 4: Relation between difference of the projection of longitudinal ISA and the actual longitudinal ISA as a function of the vertical momentum when the beam passes the solenoid.

ACKNOWLEDGMENTS

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