ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPTS028

SEARCH FOR ELECTRIC DIPOLE MOMENTS AT COSY IN JÜLICH - SPIN-TRACKING SIMULATIONS USING BMAD

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Abstract

The Jülich Electric Dipole moment Investigations (JEDI) collaboration in Jülich is preparing a direct Electric Dipole Moment (EDM) measurement of protons and deuterons. The first experiment is performed at the storage ring COSY (COoler SYnchrotron) and later a dedicated storage ring may be used for further studies. In order to analyze the data and to disentangle the EDM signal from systematic effects spin-tracking simulations are needed. Therefore a model of COSY was implemented using the software library *Bmad*. The model was successfully benchmarked using analytical predictions of the spin behavior. A crucial point regarding the data analysis is the knowledge of the orientation of the invariant spin axis with vanishing EDM at the position of the RF Wien filter. Especially its radial component is unknown and spin-tracking simulations can be used to determine this missing number. Tracking results as well as the algorithm to find the invariant spin axis will be presented in the following.

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 process is needed. A candidate for physics beyond the SM is a non-vanishing 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 SM predictions 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 electromagnetic fields enables the measurement of an EDM. The underlying experiments for charged particles need to be performed with high-precision storage rings and require an accurate measure and control of the spin and the beam motion. The JEDI collaboration is therefore investigating spin and beam effects to enable EDM studies at COSY [2,3].

SPIN DYNAMICS IN A STORAGE RING

The spin motion in presence of electromagnetic fields is described by the Thomas-BMT equation [4,5]. Since COSY is a pure magnetic machine the spin $\vec{S}$ is only influenced by magnetic fields $\vec{B}$ and the equation of motion reduces to

$$\frac{d\vec{S}}{dt} = (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}) \times \vec{S} = (\frac{q}{m} G\vec{B} + \frac{q\eta}{2m}\vec{\beta}\times\vec{B})\times\vec{S} \quad (1)$$

where $\vec{\Omega}_{MDM}$ and $\vec{\Omega}_{EDM}$ indicate the angular frequency due to the magnetic dipole moment (MDM) and the EDM respectively and G is the gyromagnetic anomaly. $\vec{\beta}$ describes the velocity ratio $\frac{v}{c}$ of the particle where c is the speed of light. Furthermore, q and m indicate the charge and mass of the particle. The effect of the EDM $\vec{d}$ enters the equation via the dimensionless proportionality factor η that is connected to the EDM by

$$\vec{d} = \eta \cdot \frac{q}{2mc}\vec{S}. \quad (2)$$

A permanent EDM results in a vertical polarization build up that is oscillating over time. In order to prevent a complete averaging out of the signal a radio-frequency (RF) device using radial electric and vertical magnetic fields, the so-called RF Wien filter, was implemented into COSY. The fields are set such that the Lorentz force cancels and therefore no beam perturbation is achieved. The EDM signal accumulates over time due to the additional phase advance the spin experiences [6–8].

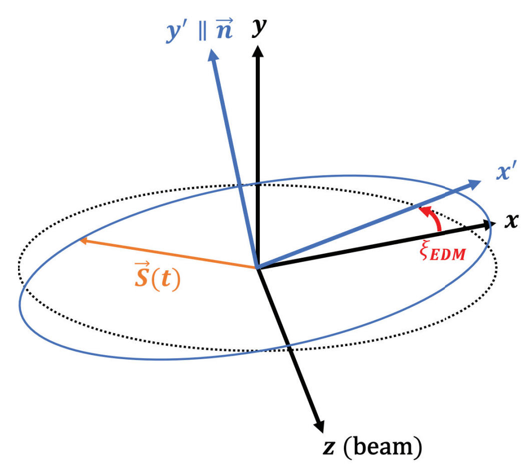

Figure 1: Due to a permanent EDM the invariant spin axis tilts in horizontal direction by the angle ξ_{EDM}.

The spin motion can be characterized by the so-called invariant spin axis $\vec{n}$. It is defined by the rotation axis around which the spin precesses. In case of an ideal ring and a vanishing EDM this axis always points in vertical direction as the spin precesses in the horizontal plane. In the presence of an EDM the invariant spin axis is tilted in the horizontal

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direction by the angle ξ_{EDM} as sketched in figure 1. This angle is directly proportional to the magnitude of the EDM and can be expressed as

$$\tan(\xi_{EDM}) = \frac{\eta\beta}{2G}. \quad (3)$$

PARTICLE AND SPIN TRACKING

Tracking Code

The underlying tool for the presented particle and spin-tracking simulations is the Fortran based software library *Bmad* [9]. It already contains basic lattice elements as dipoles, quadrupoles and sextupoles as well as the possibility to add fringe fields and misalignments to the elements. The RF Wien filter device was implemented by using superimposed static Cartesian field maps with an external time dependency.

Calculating the Invariant Spin Axis

In order to determine the polarization build up due to the EDM, it is necessary to know the orientation of the invariant spin axis. One current challenge is the lack of knowledge of the radial component of this axis that cannot be measured. A possible solution is its determination by modeling the COSY lattice and performing beam and spin tracking. To accomplish this, the spin of the reference particle is tracked for N turns which leads to an ensemble of spin vectors $\vec{s}_j$ where $j \in \mathbb{N}$ and $j \in [1, N]$. For each possible configuration of three chosen spin vectors $(\vec{s}_1, \vec{s}_2, \vec{s}_3)$ an invariant spin axis $\vec{n}_i$ is calculated as follows.

$$\vec{u}_i = \vec{s}_{2,i} - \vec{s}_{1,i} \quad (4)$$

$$\vec{v}_i = \vec{s}_{3,i} - \vec{s}_{1,i} \quad (5)$$

$$\vec{n}_i = \frac{\vec{v}_i \times \vec{u}_i}{|\vec{v}_i \times \vec{u}_i|} \quad (6)$$

Figure 2 shows a schematic description of the method. The invariant spin axis is then calculated as the mean of all $\vec{n}_i$ vectors. Figure 3 shows the spin distribution after tracking trough the COSY lattice including the misalignments of dipoles and quadrupoles as well as an illustration of individual spin vectors $\vec{s}_j$, the vectors $\vec{n}_i$ and the average invariant spin axis $\langle\vec{n}\rangle$.

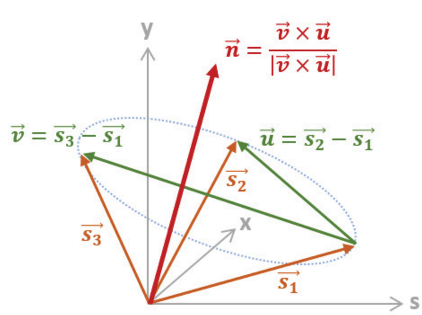

Figure 2: Method for calculating the invariant spin axis from three chosen spin vectors.

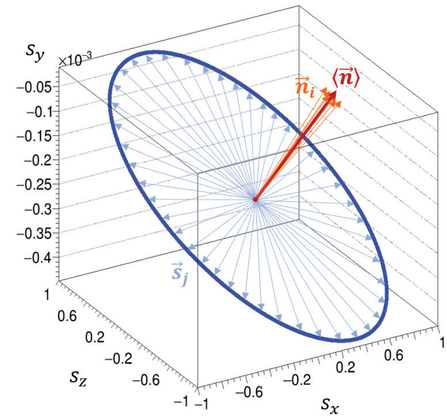

Figure 3: Illustration of the method to calculate the invariant spin axis (red). The spin distribution resulting from misaligned magnets is shown in blue and the average invariant spin axis is indicated in red.

The precision of this method can be easily investigated by performing a simulation assuming a non-zero EDM value and comparing the resulting invariant spin axis with the theoretical prediction of equation 3. Taking an input value of $\eta = 0.0002$ (corresponds to and EDM of $|\vec{d}| \approx 10^{-18}\ e \cdot \text{cm}$) leads to an invariant spin axis of

$$\langle\vec{n}\rangle = \begin{pmatrix} -0.321269108 \cdot 10^{-3} \pm 7.636 \cdot 10^{-9} \\ 0.999999948393 \pm 2.5 \cdot 10^{-12} \\ 2.568 \cdot 10^{-9} \pm 1.6878 \cdot 10^{-8} \end{pmatrix}. \quad (7)$$

Equation 3 gives a value of $n_x = -0.32127 \cdot 10^{-3}$ which corresponds to the calculated horizontal component of the invariant spin axis. As expected, the longitudinal component is zero within the error.

Simulations for Precursor Experiment

For the precursor experiment at COSY the so-called EDM resonance strength ε_{EDM} is measured. It is defined as the ratio of the angular frequency of the vertical polarization oscillation Ω_{Py} and the orbital angular frequency Ω_{rev}

$$\varepsilon_{EDM} = \frac{\Omega_{Py}}{\Omega_{rev}}. \quad (8)$$

The measurement uses the RF Wien filter as well as the longitudinal field of a solenoidal magnet to manipulate the spin motion. The vertical polarization build up is measured for each setting of RF Wien filter rotation and solenoid field [10]. This results in a two-dimensional map as shown in figure 4 where ϕ_{WF} denotes the rotation angle of the RF Wien filter. χ_{Sol} relates to the spin rotation angle due to the solenoid field. The EDM resonance strength can be analytically described by a parabolic function and the following function can be used to fit the measurement results [11]

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$$\varepsilon_{EDM}^2 = A\cdot(\phi_{WF}-\phi_{0,WF})^2+B\cdot\left(\frac{\chi_{Sol}}{2\sin(\pi\nu_s)}+\chi_{0,Sol}\right)^2+C. \tag{9}$$

where ν_s denotes the unperturbed spin tune[1]. According to theoretical predictions, the fit parameters A and B should be equal and C is supposed to be zero. The parameters $\phi_{0,WF}$ and $\chi_{0,Sol}$ indicate the point of minimal resonance strength. In other words, $\phi_{0,WF}$ is a measure for the horizontal component of the invariant spin axis, including the effect of the EDM, as well as all systematic effects that tend to affect the spin motion and, as a consequence, tilt the invariant spin axis. Performing spin tracking with a vanishing EDM and taking the misalignments of the COSY dipoles and quadrupoles into account is a first approach of modeling the experimental conditions. Figure 4 shows the resulting map as well as the fitted function using equation 9. Figure 5 displays the projection to the horizontal plane in order to clearly illustrate the shift of the minimum of the fit.

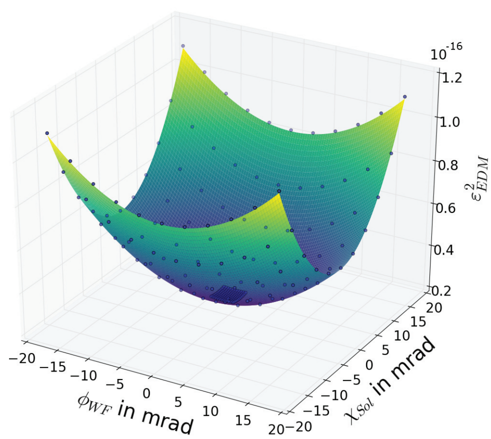

Figure 4: Simulation results assuming a vanishing EDM and taking magnet misalignments into account. Equation 9 was used for fitting and the fit result is displayed as well.

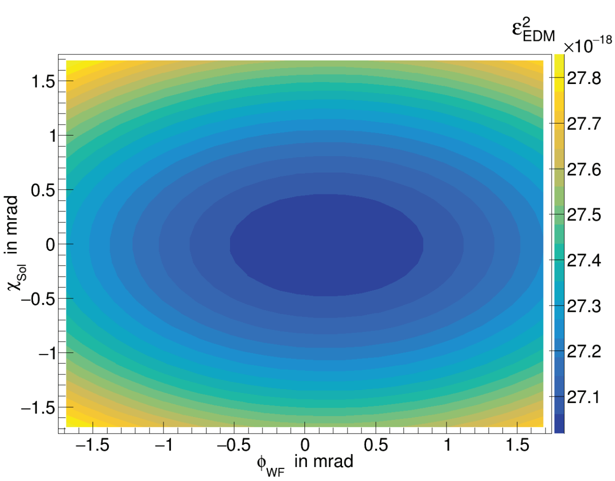

Figure 5: Horizontal projection of the fit shown in figure 4.

[1] number of spin revolutions per turn

In order to compare the simulation results with the measurement, the fit values to the simulated points as well as the preliminary results of the first measurement are listed in table 1 [12]. The errors of the fit to the measured data may be further reduced if one takes data at more points of the map. Since an EDM only leads to a tilt of the invariant spin axis in the horizontal direction and does not affect the longitudinal component, the value of $\chi_{0,Sol}$ is only influenced by longitudinal magnetic fields originating from the solenoid and other systematic sources. Comparing the $\chi_{0,Sol}$ values in table 1 with each other there is a huge difference of three orders of magnitude. One can therefore conclude that the simulation model, which so far includes only the misalignments of dipoles and quadrupoles, is missing dominant systematic effects that lead to a net longitudinal magnetic field and thus produce a larger longitudinal component of the invariant spin axis. Nevertheless, the fit results of the simulation are in agreement with the calculated invariant spin axis using the method of the previous section that results in

$$\langle\vec{n}\rangle = \begin{pmatrix} 0.151519\times10^{-3}\pm2.17\times10^{-9} \\ 0.999999985\pm5\cdot10^{-13} \\ 1.9463\cdot10^{-5}\pm4.86\cdot10^{-9} \end{pmatrix}. \tag{10}$$

Table 1: Fit Parameters of Simulation and Measurement

	Simulation	Measurement
$\phi_{0,WF}$	0.15328 ± 0.0176 mrad	-3.7 ± 0.04 mrad
$\chi_{0,Sol}$	0.01093 ± 0.00869 mrad	-6.96 ± 0.04 mrad

CONCLUSION

The JEDI collaboration investigates the EDM of deuterons at COSY performing a high-precision experiment. To distinguish the EDM signal from systematic effects, spin-tracking simulations are needed. Using the software library *Bmad* a model of COSY and a method to extract the invariant spin axis were implemented. The model was benchmarked and the spin tracking results show high compatibility with the theoretical predictions. As first order effects magnet misalignments were included in the model in order to compare the simulation results with the first measurements at COSY. The comparison shows that the model misses a net longitudinal magnetic field which is possibly induced by longitudinal field components of the magnet fringe fields for off-center particles. Additionally, longitudinal fields may occur due to the narrow positioning of the COSY magnets and the resulting fringe field modification. As a next step these effects will be investigated and added to the simulation model.

ACKNOWLEDGEMENT

This work has been performed in the framework of the JEDI and CPEDM collaboration. The authors wish to acknowledge the support by the European Research Council via the ERC Advanced Grant "srEDM" (No. 694340).

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