Spin Physics (SPIN2014)
International Journal of Modern Physics: Conference Series
Vol. 40 (2016) 1660099 (6 pages)

DOI: 10.1142/S2010194516600995

Estimation of Systematic Errors for Deuteron Electric Dipole Moment Search at COSY

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Published 29 February 2016

An experimental method which is aimed to find a permanent EDM of a charged particle was proposed by the JEDI (Jülich Electric Dipole moment Investigations) collaboration. EDMs can be observed by their 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 it 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 affects the beam and the spin motion. It is planned to use a RF Wien filter for the precusor experiment. In this paper the simulations of the systematic effects for the RF Wien filter device method will be discussed.

1. The RF Wien Filter Method to Measure an EDM

One of the possibilities to search for a permanent deuteron EDM at COSY is the so-called RF Wien filter method.[1] It was proposed to use a Wien filter with a strong radial electric field. The Lorentz force inside such a device equals to zero in the particle rest frame, and therefore it has no influence on the EDM. However, the interaction of the magnetic dipole moment (MDM) with the combined motional and direct magnetic fields leads to an additional kick in the spin precession. This MDM kick, together with the interaction of the EDM with the motional electric field in COSY ring, yields the spin rotation around the radial axis and produces a build-up of a vertical or horizontal polarization, depending on the initial spin orientation, which increases linearly with time. In the absence of the RF Wien filter the same EDM interaction in the ring results in the small oscillating signal, which doesn't grow with time. The spin motion is described by the well-known Thomas-BMT equation with included EDM terms.[2]

$$\frac{d\vec{S}}{dt} = \vec{S} \times (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}),$$
$$\vec{\Omega}_{MDM} = \frac{q}{m}\left\{G\vec{B} + \frac{\gamma G}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{B}) - \left(G - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right\},$$
$$\vec{\Omega}_{EDM} = \frac{\eta q}{2mc}\left\{\vec{E} - \frac{\gamma}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{E}) + c\vec{\beta}\times\vec{B}\right\} \tag{1}$$

where $\vec{S}$ denotes the spin vector in the particle rest frame in units of $\hbar$, t is the time in the laboratory system, β and γ are the relativistic Lorentz factors. q and m are the charge and the mass of the particle, respectively. $\vec{B}$ and $\vec{E}$ are the magnetic and electric fields in the laboratory system. Two angular frequencies $\vec{\Omega}_{MDM}$ and $\vec{\Omega}_{EDM}$ are defined with respect to the momentum vector. The dimensionless parameters G and η are related to the magnetic and electric dipole moments of the particle in the following way:

$$\vec{\mu} = g\frac{q\hbar}{2m}\vec{s} = (G+1)\frac{q\hbar}{m}\vec{s}$$
$$\vec{d} = \eta\frac{q\hbar}{2mc}\vec{s} \tag{2}$$

The RF Wien filter has a radial electric E_x and a vertical magnetic B_y field. It must be operated on a harmonic K of the spin motion,

$$f_{WF} = |K + G\gamma| f_{rev}, \tag{3}$$

where f_{WF} is the frequency of the harmonically excited RF Wien filter and f_{rev} is the beam revolution frequency. That device should not excite any betatron oscillations in the machine, so the alignment of it and other elements in COSY plays a crucial role in the experiment. This paper will mainly focus on investigation of systematic effects that happen in the presence of any distortions of the COSY magnets or the Wien filter itself. The mismatch between the resonance and the operating frequencies will be cosidered because it also spoils the polarization build-up. All systematic studies are performed in the new simulation code MODE that was recently developed by JEDI collaboration.[3]

2. The Simulations with Misalignments

2.1. *The RF Wien filter rotations*

The rotation of the RF Wien filter around longitudinal axis yields a horizontal component of the magnetic field B_x, which, in turn, causes the vertical betatron oscillations of the beam. The spin recieves an additional kick due to the MDM

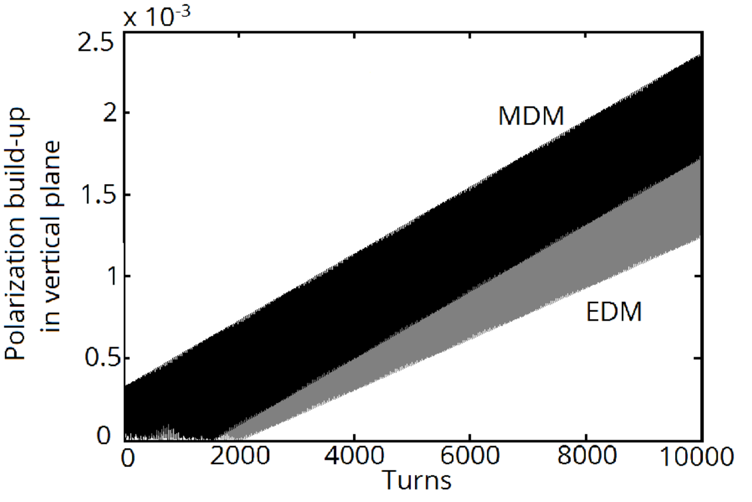

Fig. 1. The polarization build-up in vertical plane. The initial spin direction of the deuteron is longitudinal. In black: the MDM interaction with the field of the longitudinally rotated Wien filter in the absence of the EDM. The rotation angle is 10^{-4}rad. In grey: the EDM interaction with the motional electric field, when the Wien filter is perfectly aligned. An EDM of $2.6 \cdot 10^{-19} e \cdot \text{cm}$ was assumed.

interaction with B_x according to Thomas-BMT equation. This kick works in the same way as an EDM interaction with the motional electric field in the ring (see Fig. 1). It is clearly visible that the rotation of the device leads to the same amount of the polarization build-up, which could be produced by the EDM of the order of $10^{-19} e \cdot \text{cm}$. The build-up of the polarization per turn scales linearly with the value of the angle of the RF Wien filter rotation, as well as the false EDM signal, which this rotation generates. The spin experiences fast (g-2) precession, which are modulated by the RF Wien filter. That is why one sees two broad bands in Fig. 1, and not a single line. The wideness of the bands is proportional to the value of the EDM. In the following simulation η that is equal to 10^{-4} will be used, which corresponds to the EDM of $2.6 \cdot 10^{-19} e \cdot \text{cm}$.

2.2. *Misalignments of the ring elements*

The next step one should take, is to consider the effect of the non-vanishing misalignments of the magnets in the machine. The presence of the misalignments tilts the initially vertical direction of the spin closed orbit. This induces the similar false build-up of the polarization, which was described above. The present misalignments at COSY are of the order of 0.1 mm (or mrad for rotations). They were randomly distributed in the simulation program. The typical random seed coincides with the result, which is shown in Fig. 2. There was no orbit correction made during the

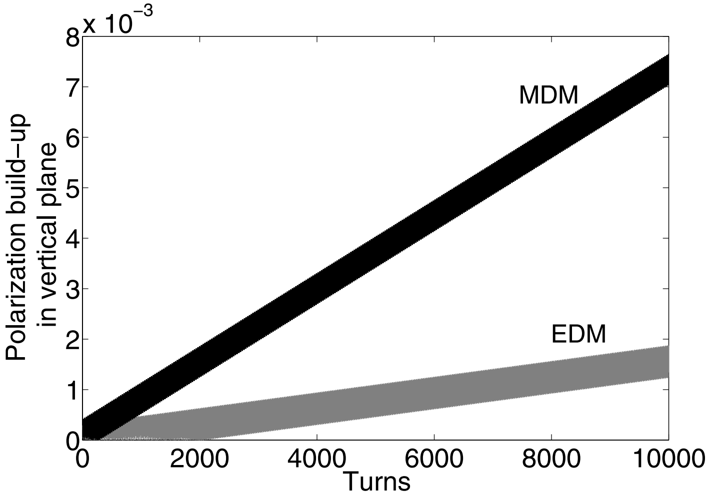

Fig. 2. The polarization build-up in vertical plane. The initial spin direction of the deuteron is longitudinal. In black: The polarization build-up due to the MDM interaction with imperfection fields of the misaligned magnets with RF Wien filter on. In grey: the EDM interaction with the motional electric field in the absence of imperfections. The EDM was $2.6 \cdot 10^{-19} e \cdot \text{cm}$.

simulation. However, with closed orbit correction algorithm used at COSY the systematic limit on the EDM determination will be of the order of $10^{-19} e \cdot \text{cm}$.[5]

2.3. *Frequency mismatch*

As it was mentioned above, the RF Wien filter must be operated exactly at the spin resonance. What happens, if there is a mismatch between the operating and the resonance frequencies? One can denote this mismatch by

$$\Delta = \frac{f_{WF}}{f_{res}}, \tag{4}$$

where f_{WF} and f_{res} are the operating Wien filter and the spin resonance frequencies respectively. An EDM of $10^{-21} e \cdot \text{cm}$ was used in the simulation. Four different mismatches were considered with the largest one of 10^{-4} and the smallest one of 10^{-7}. Here η parameter was set two orders of magnitude lower and was equal to 10^{-6}. The resulting polarization build-ups are plotted in Fig. 3.

One can see that the polarization does not grow linearly anymore, when two frequencies do not match, but indeed oscillates. The resonance condition must be fulfilled with the great precision. In the case, when $\Delta = 10^{-7}$ the slope of the polarization build-up coincides with the theoretically calculated value. This indicates that one should set the frequency of the RF Wien filter with the precision of 10^{-7} for the EDM of $10^{-21} e \cdot \text{cm}$. However, that constraint also scales linearly with the value of the EDM, and for the EDM of the order of $10^{-20} e \cdot \text{cm}$ one can afford to have a mismatch at the level of 10^{-6}.

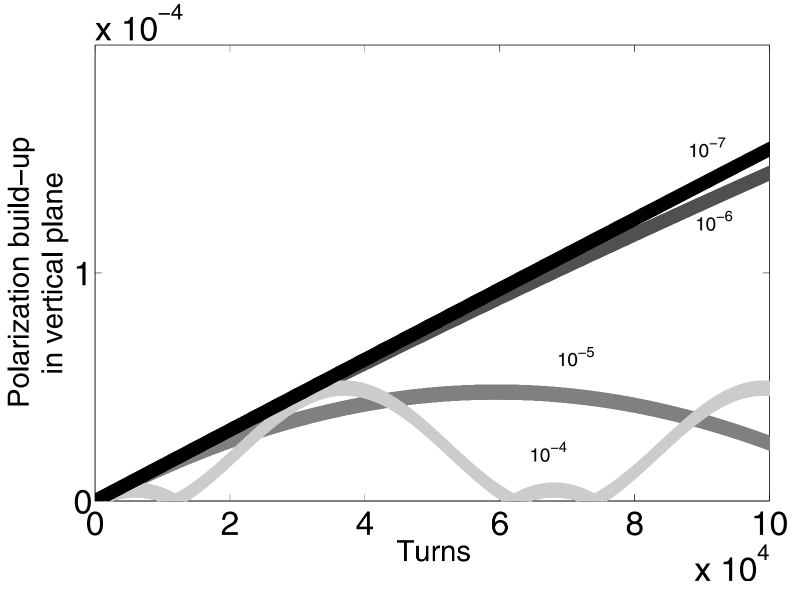

Fig. 3. The polarization build-ups due to the EDM interaction with the motional electric field for different values of the mismatch between the spin resonance and the operating Wien filter frequencies. a) $\Delta = 10^{-7}$ b) $\Delta = 10^{-6}$, c) $\Delta = 10^{-5}$, d) $\Delta = 10^{-4}$. An EDM was equal to $2.6 \cdot 10^{-21} e \cdot \mathrm{cm}$.

3. Conclusion

One of the possible ways to measure an EDM at the precursor experiment at COSY was considered. The representation of the RF Wien filter was realized in MODE[3] program. The systematic effects, which limit the potential sensitivity,[4] were studied.

The impact of the rotations of the Wien filter was investigated. Firstly, the EDM-like signal was generated by the MDM interaction with the rotated vertical magnetic field of the Wien filter. Secondly, the situation with the pure EDM build-up for the untilted device was considered. It was shown that the rotations of the RF Wien filter around the longitudinal axis yields the same build-up of the vertical polarization as caused by the EDM interaction with the motional electric field in COSY ring.

The spin motion was examined when the misalignments and rotations of the magnets of COSY took place. Two types of tracking were performed for that reason, one with the EDM and a perfect orbit and another without one for the distorted case. The build-ups of polarization were plotted aganst the turn number for both situations and later compared in order to get the systematic limit on the current COSY configuration.

The mismatch between the operating frequency of the RF Wien filter and the spin resonance frequency was considered. Four particular situations with different relative frequency mismatches were tested in the simulation. The resulting polarization build-ups were compared. The deviation from linear behaviour, which prevents the possibility of polarization measurements, was demonstrated. It was presented that one must pay significant attention to the fullfilment of the resonance condition.

In summary, all three simulation results indicate the same systematic limit, for the present situation at COSY, of the order of $10^{-19} e \cdot \mathrm{cm}$. This is a starting point for the precursor experiment that is planned to be cunducted in the next 2 years. Based on this, one should think of an installation of a modern orbit correction system and on a way to control and keep the frequency of the RF Wien filter with the maximum achievable precision. Further simulation work will be done towards the implementation of an orbit correction algorithm in MODE program. Field errors of the Wien filter must be considered and the effect caused by them should be calculated.

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