BEAM AND SPIN DYNAMICS FOR STORAGE RING BASED EDM SEARCH*

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Abstract

Full spin-tracking simulations of the entire experiment are absolutely crucial to explore the feasibility of the planned storage ring EDM (Electric Dipole Moment) experiments and to investigate systematic limitations. For a detailed study during the storage and build-up of the EDM signal, one needs to track a large sample of particles for billions of turns. In addition, benchmarking experiments have to be performed to check and to further improve the simulation tools.

INTRODUCTION

Permanent EDMs of fundamental particles violate both time invariance T and parity P. Assuming the CPT theorem this implies CP violation. The Standard Model (SM) predicts non-vanishing EDMs. Their magnitudes, however, are expected to be unobservably small with current experimental techniques. The discovery of a non-zero EDM would be a signal for new physics and could explain the matter-antimatter asymmetry observed in our Universe. Different approaches to measure EDMs of charged particles are pursued at Brookhaven National Laboratory (BNL) [1] and Forschungszentrum Jülich [2] with an ultimate goal to reach a sensitivity of 10^{-29} e·cm in a dedicated storage ring. The Jülich-based JEDI Collaboration (Jülich Electric Dipole moments Investigations) has been formed to exploit and demonstrate the feasibility of such a measurement and to perform the necessary R&D work towards the design of a dedicated storage ring [3]. As a first step R&D work at COSY is pursued. Subsequently, an EDM measurement of a charged particle will be performed at COSY with limited sensitivity. On a longer time scale, the design and construction of a dedicated storage ring will be carried out.

EXPERIMENTAL METHOD

The principle of every EDM measurement (e.g., neutral and charged particles, atoms, molecules) is the interaction of the particles' electric dipole moment with an electric field. In the center-of-mass system of a particle electric dipole moments $\vec{d}$ couple to the electric fields, whereas magnetic dipole moments $\vec{\mu}$ (MDM) couple to magnetic fields.

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The spin precession in the presence of both electric and magnetic fields is given by:

$$\frac{d\vec{S}}{dt} = \vec{d} \times \vec{E}^* + \vec{\mu} \times \vec{B}^*. \tag{1}$$

$\vec{E}^*$ and $\vec{B}^*$ denote the electric and magnetic fields in the rest frame of a particles. In case of moving particles in a circular accelerator or storage ring, the spin motion is covered by the Thomas-BMT equation and its extension for EDM:

$$\frac{d\vec{S}}{dt} = \vec{S} \times (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}),$$

$$\vec{\Omega}_{MDM} = \frac{q}{m}\left[G\vec{B} - \frac{\gamma G}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{B}) - \left(G - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right],$$

$$\vec{\Omega}_{EDM} = \frac{\eta q}{2mc}\left[\vec{E} - \frac{\gamma}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{E}) + c\vec{\beta}\times\vec{B}\right]. \tag{2}$$

$\vec{S}$ in this equation denotes the spin vector in the particle rest frame in units of $\hbar$, t the time in the laboratory system. β and γ are the relativistic Lorentz factors, q and m the charge and the mass of the particle, respectively. $\vec{E}$ and $\vec{B}$ denote the electric and magnetic fields in the laboratory system. Two angular frequencies $\vec{\Omega}_{MDM}$ and $\vec{\Omega}_{MDM}$ are defined with respect to the momentum vector. The gyromagnetic anomaly $G=(g-2)/2$ with the Landé g-factor and η are dimensionless and related to the magnetic and electric dipole moments of the particle as follows:

$$\vec{\mu} = 2(G+1)\frac{q\hbar}{2m}\vec{S}, \vec{d} = \eta\frac{q\hbar}{2mc}\vec{S}. \tag{3}$$

In a planar storage ring the spin precession in the horizontal plane is governed by the MDM. If an EDM exists, the spin vector will experience an additional torque. The resulting vertical spin component, proportional to the size of the EDM, will be measured by scattering the particles of the stored beam at an internal target and analyzing the azimuthal distribution of the scattered particles. A coherent buildup of the vertical polarization only takes place within the time the spins of the particle ensemble stays aligned. Since the spin tune is a function of the betatron and synchrotron amplitudes of the particles in the six-dimensional phase space, spin decoherence is caused by beam emittance and momentum spread of the beam and leads to a gradual decrease of the polarization buildup rate in the vertical direction. To reach the anticipated statistical sensitivity of 10^{-29} e·cm a Spin Coherence Time (SCT) of 1000 s has to be reached. The mean challenge of such kind of experiment is a very small expected vertical component of the spin excited by the EDM and the relatively large contribution by false spin rotations via the MDM due the field and misalignments errors of accelerator elements.

Starting from Equation 2, different approaches are possible to excite spin rotations via the electric dipole moment:

1. Frozen spin method [4], where the bending fields in a storage ring are adjusted according to the particle momentum in such a way that the longitudinally polarized spins of the particle beam are kept aligned ("frozen") with their momenta. If the particle has an EDM along its spin direction, the E-fields in the rest frame of the particles will rotate the spin into the vertical direction. This change of the vertical component of the beam polarization from early to late storage times is the signature of the EDM signal.
2. Resonant method [5, 6], were an RF-ExB dipole runs at a frequency tuned to the spin tune ($\gamma G \pm K$, K integer). In the Wien filter mode the ratio of the electric and magnetic fields are chosen in a way, that the Lorentz force cancels: $\vec{E}/c = -\vec{\beta} \times \vec{\mathrm{B}}$. This means, that the RF Wien filter will not influence the EDM directly. It does, however, modulate the horizontal spin precession turn by turn. Together with the interaction of the EDM with the motional electric field in the rest of the ring, this frequency modulation is able to rotate the spin around the radial axis and leads to an accumulation of the EDM signal.

BEAM AND SPIN DYNAMICS

For a detailed study during the storage and buildup of the EDM signal, one needs to track a large sample of particles for billions of turns. Given the complexity of the tasks, particle and spin dynamics simulation programs must be benchmarked and tracking results compared to beam experiments, to ensure the required accuracy of the obtained simulation results. The COSY INFINITY [7] and MODE [8] simulation programs are utilized for this purpose, both based on map generation using differential algebra and the subsequent calculation of the spin-orbital motion for an arbitrary particle.

Integrating programs, solving equations of particle and spin motion in electric and magnetic fields using Runge-Kutta integration, have also been used for benchmarking [9].

In a first step the development and implementation of time-dependent transfer maps as well as the EDM extension to spin motion were tested and used to investigate the resonant method and its systematic limitations with COSY INFINITY and MODE.

Investigations of Systematic Effects Studies for the Resonance Method

Main sources of systematic errors for the resonance method are the alignment of the RF Wien filter with respect to the invariant spin field, opening angle of spin ensemble, field quality (fringe fields), the relative frequency slip of the RF Wien filter and the closed orbit deviation of the beam due to misalignments and field errors of ring magnets. The spin motion including these systematic errors has been investigated for the resonance method in detail [10, 11]. The resulting closed orbits can be corrected by the orbit correction system to suppress false spin rotations via the MDM [12]. From these simulations the present estimate for the systematic EDM limit utilizing the resonance method at COSY is in the order of $d = 10^{-19}$ e·cm for a remaining orbit excitations below the millimeter level, a rotation of the RF Wien filter of 10^{-4} rad and relative mismatch between the operating frequency of the RF Wien filter and the spin resonance frequency of less than 10^{-5}. In order to improve the systematic EDM limit for this method the closed orbit correction system of COSY has to be improved significantly, the relative frequency slip of the RF-ExB dipole stabilized and the RF Wien filter aligned to the invariant spin axis with the maximum achievable precision.

A prototype RF Wien filter has been developed and successfully commissioned with low power to carry out a feasibility test [13]. The device was operated at the $f_{rev}\,|\gamma G - 1|$ harmonics of the spin precession frequency at roughly 871 kHz. A series of fixed frequency scans have been taken during a JEDI beam time at COSY to determine the dependence of spin resonance strength upon the betatron tune. Once the RF Wien filter was matched at appropriate betatron and spin resonance sidebands, the ion optics of the accelerator was moved towards different vertical betatron tunes. At each tune similar scans were taken for comparison with an already installed RF solenoid and a pure magnetic RF dipole. As expected, the matched RF Wien filter as well as the RF solenoid didn't excite coherent betatron oscillations whereas the spin motion for a pure magnetic RF dipole is dominated by the influence of the induced coherent beam oscillations. Experimentally, this effect has already been observed by experiments of the SPIN@COSY Collaboration [14].

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Experimental and Theoretical Studies of Spin Coherence Time

Effective measures to counteract spin decoherence is phase-space cooling, beam bunching and multipole correction. Especially the adjustment of beam chromaticity by sextupole magnets at COSY has been studied theoretically and experimentally [12, 15]. For the measurements and the results discussed below a common experimental setup of COSY has been used with a polarized deuteron beam of roughly 10^9 particles, electron-cooled beams to reduce the equilibrium beam emittance and momentum spread, accelerated to a beam momentum of 970 MeV/c and bunched by an RF cavity. An RF solenoid induced spin resonance was employed to rotate the spin by 90° from the initially vertical direction into the horizontal plane. Three different families of sextupole magnets located in the arcs of COSY were adjusted to find the best setting for long SCT. It has been demonstrated experimentally that the SCT of a horizontally polarized deuteron beam at COSY can be substantially extended to roughly 1000 s through a combination of sextupole fields by adjusting the beam chromaticities $\xi_{x,y}$ together with beam bunching and electron cooling [16].

Simulations with COSY INFINITY confirmed the experimental results [12]. Highest SCT can be reached by adjusting the beam chromaticities $\xi_{x,y}$. This way the path-length change induced by the betatron motion is reduced. In addition the parameter κ should be minimized to cancel the path-length change due to second order momentum deviations:

$$\kappa \equiv \left[\alpha_1 + \frac{3}{2\gamma^2}\left(\beta^2 - \left(\alpha_0 - \frac{1}{\gamma^2}\right)\right)\right], \qquad (4)$$

where α_0 and α_1 are the first and second order momentum compaction factor, respectively. Both chromaticities and the second order momentum compaction factor α_1 can be adjusted by the three sextupole families in the arcs of COSY.

CONCLUSION

Different proposals to perform a first direct EDM measurement at COSY will be further investigated by spin tracking simulations in order to quantify the systematic limits and finally perform a first EDM measurement at COSY. For the design study of a dedicated EDM storage ring, lattice design and spin tracking to identify the systematic EDM limit of the experimental method in conjunction with the design of all accelerator elements will be the major task for the JEDI collaboration in the upcoming years.

To achieve the unprecedented precision of the EDM measurement robust and advanced numerical tracking codes are required for exploring various systematic effects. Also sophisticated lattice design tools for storage rings with all electrostatic elements as well as combined magnetic and electric elements have to be applied. To identify the best approach using numerical simulation codes a satellite meeting during the IPAC15 has been organized [17]. The discussions at this meeting included benchmarking of simulation codes against first-principle based models as well as experimental results.

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