SEARCHING ELECTRIC DIPOLE MOMENTS IN STORAGE RINGS - CHALLENGES, STATUS AND COMPUTATIONAL NEEDS - *

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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 buildup of the EDM signal, one needs to track a large sample of particles for billions of turns. Existing spin tracking programs have to be extended to properly simulate spin motion in presence of an EDM. In addition, benchmarking experiments are performed at the Cooler Synchrotron COSY to check and to further improve the simulation tools. Finally, the layout of a dedicated storage ring has to be optimized by a full simulation of particle and spin motion.

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. Hence, 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 proposed with an ultimate goal to reach a sensitivity of 10^{-29} e·cm in a dedicated storage ring [1,2,3]. 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 [4]. As a first step R&D work at the Cooler Synchrotron COSY is pursued. Subsequently, an EDM measurement of a charged particle will be performed at COSY with limited sensitivity [5]. On a longer time scale, the design and construction of a dedicated EDM 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 particles electric dipole moments $\vec{d}$ couple to the electric fields, whereas magnetic dipole moments $\vec{\mu}$ (MDM) couple to magnetic fields.

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

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

$\vec{E}^*$ and $\vec{B}^*$ denote the electric and magnetic fields in the rest frame of a particle.

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 [6]:

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

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

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

$\vec{S}$ 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 mass of the particle, respectively. $\vec{E}$ and $\vec{B}$ denote the electric and magnetic fields in the laboratory system. Two angular frequencies $\vec{\Omega}_{\mathrm{MDM}}$ and $\vec{\Omega}_{\mathrm{MDM}}$ 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:

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

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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 major 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 [7], where the electrostatic and magnetic 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. For protons pure electrostatic bending fields are sufficient to freeze the spin at a magic momentum of roughly 701 MeV/c [1]. If the particle has an EDM along its spin direction, the electrostatic 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. Quasi-frozen-spin method [8], where the anomalous magnetic moment of the particles has to have a small negative value like for deuterons. In this case electric and magnetic field deflectors can be spatially separated. The spins oscillate around the momentum direction in the horizontal plane back and forth every time the particle passes through a magnetic or an electrostatic field. The spin oscillations of individual particles compensate each other with respect to the momentum vector in the magnetic and electrostatic part of the ring. Due to the low value of the anomalous magnetic moment of deuteron, an effective contribution to the expected EDM effect is reduced only by a few percent compared to the frozen-spin method.
3. Resonant method [5,9], were an RF ExB dipole runs at a frequency tuned to the spin tune ($\gamma G \pm K$, K integer). In Wien filter mode the ratio of the electric and magnetic fields are chosen in a way that the Lorentz force cancels: $\vec{E}/c = -\vec{\beta}\times\vec{B}$. This means, that the RF Wien filter will not influence the EDM directly. It does, however, modulate the horizontal spin precession via the MDM 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 tracking programs must be benchmarked and simulation results compared to beam experiments, to ensure the required accuracy of the obtained results. The COSY Infinity [10] and MODE [11] 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. In a first step the development and implementation of time-dependent transfer maps as well as the EDM extension to spin motion were benchmarked and used to investigate the resonant method and its systematic limitations. Integrating programs, solving equations of particle and spin motion in electric and magnetic fields using Runge-Kutta integration, have also been used for benchmarking [12].

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 International Particle Accelerator Conference IPAC'15 in Richmond (VA, USA) has been organized [13]. The aim of this meeting was to review different advanced numerical tracking codes for exploring various systematic effects. In addition various lattice design codes with all electrostatic as well as combined magnetic and electric elements have been discussed. The following capabilities are required:

- Accurate description of all ring elements including fringe fields.
- Allowing various error inputs for systematics investigation.
- Accurate implementation of RF spin manipulation elements.
- Calculation of orbital and spin motion with a high accuracy for billion orbital revolutions.
- User friendly graphic interfaces for extracting physical information from tracking data (e.g., orbit, betatron tune, and spin tune from tracking data).

The discussions at this meeting included benchmarking of simulation codes against first principle based models as well as experimental results. A second meeting will be organized during International Particle Accelerator Conference IPAC'16 in South Korea to further discuss extensions and benchmarking of the various simulation programs.

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 the Cooler Synchrotron COSY has been studied theoretically and experimentally [14,15]. 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 more than 1000 s through a combination of sextupole fields by adjusting the beam chromaticities $\xi_{x,y}$ together with beam bunching and electron cooling [15].

Simulations with COSY Infinity confirmed the experimental results [14]. 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 path length change due to second order momentum deviations has to be minimized. Both chromaticities and the second order momentum compaction factor can be adjusted accordingly by the three sextupole families in the arcs of COSY.

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 [16,17]. The resulting closed orbits can be corrected by the orbit correction system of COSY to suppress false spin rotations via the MDM [16]. From these simulations the present estimate for the systematic EDM limit utilizing the resonance method at the Cooler Synchrotron 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} [17]. 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.

Lattice Design of a Dedicated Storage Ring

Presently, the two different approaches to design a dedicated deuteron EDM ring are investigated, the frozen and the quasi-frozen-spin method. The proposed quasi-frozen-spin lattice leads to a simplified design of electrostatic and magnetic bending elements [18], because magnetic and electric bending elements can be spatially separated. Additional systematic spin rotations due to this separation of bending elements have to be carefully studied. In addition a frozen-spin lattice is under investigation with combined magnetic and electrostatic field deflectors. Presently different lattice configurations are investigated ranging for bending radii between 30 and 20 m. The required electric field strength for a 1 GeV/c deuteron beam reaches 4 to 8 MV/m with a magnetic field of roughly 0.15 to 0.3 T.

To confirm the feasibility of the different lattice structures, beam and spin tracking simulation are performed using COSY Infinity and MODE.

CONCLUSION

Different proposals to perform a first direct EDM measurement at the Cooler Synchrotron 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 are a major task for the JEDI collaboration in the upcoming years. This requires dedicated tools for lattice design with electrostatic and magnetic field elements.

A very accurate description of all ring elements including fringe fields are indispensable for beam and spin tracking simulations in order to achieve the intended accuracy of the planned EDM measurements.

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