

PROJECT OVERVIEW AND COMPUTATIONAL NEEDS TO MEASURE ELECTRIC DIPOLE MOMENTS AT STORAGE RINGS

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Abstract

Different approaches to measure Electric Dipole Moments (EDMs) of proton, deuteron and light nuclei are pursued at Brookhaven National Laboratory (BNL) and Forschungszentrum Jülich (FZJ) with an ultimate goal to reach a sensitivity of 10^{-29} e·cm in a dedicated storage ring. As an intermediate step, a first direct EDM measurement of protons and deuterons at 10^{-24} e·cm sensitivity level will be carried out in a conventional storage ring, the Cooler Synchrotron COSY at FZJ [1].

Full spin-tracking simulations of the entire experiment are absolutely crucial to explore the feasibility of the planned storage ring EDM experiments and to investigate systematic limitations. For a detailed study of particle and spin dynamics during the storage and buildup of the EDM signal, one needs to track a large sample of particles for billion of turns.

INTRODUCTION

Permanent EDMs of fundamental particles violate both time invariance $\mathcal{T}$ and parity $\mathcal{P}$. 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 in the near future. Hence, the discovery of a non-zero EDM would be a signal for “new physics” beyond the SM. It is mandatory to measure EDMs on different species of particles in order to disentangle various sources of CP violation. While neutron EDM experiments are pursued at many different places worldwide, no such direct measurements have been conducted yet for protons and other light nuclei due to special difficulties of applying electric fields on charged particles. EDM experiments with charged particles are only possible at storage rings.

As a first step towards EDM searches in storage rings we proposed R&D work to be carried out at the Cooler Synchrotron COSY [2,3], then perform a first direct EDM measurement of a charged particle in a storage ring at the Cooler Synchrotron COSY, and on a longer time scale construct a dedicated storage ring [3,4].

The COSY Infinity simulation program [5] and its updates are used to simulate beam and spin motion in storage rings. To study subtle effects and simulate the particle and spin dynamics during the storage and buildup of the EDM signal, one needs custom-tailored fast trackers capable of following up to 100 billion turns for samples of up to 10^6 particles. Given the complexity of the tasks, particle and spin dynamics simulations

performed with COSY Infinity must be benchmarked with other simulation programs and experiments performed at the Cooler Synchrotron COSY, to ensure the required accuracy of the obtained simulation results.

EDM MEASUREMENTS AT STORAGE RINGS

Principle

The principle of every EDM measurement (e.g., neutral and charged particles, atom, molecule) is the interaction of an electric field with the dipole moment of the particle. In the center-of-mass system of a particle electric dipole moments $\vec{d}$ couple to electric fields, whereas magnetic dipole moments $\vec{\mu}$ couple to magnetic fields. The spin precession in the presence of both electric and magnetic fields is given by:

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

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

$$\begin{aligned} \frac{d\vec{S}}{dt} &= \vec{\Omega} \times \vec{S} \\ \vec{\Omega} &= \frac{eh}{mc} \left\{ G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1} \right) (\vec{v} \times \vec{E}) + \frac{\eta}{2} (\vec{E} + \vec{v} \times \vec{B}) \right\}. \end{aligned} \quad (2)$$

$\vec{E}$ and $\vec{B}$ denote the electric and magnetic fields in the laboratory system, with the constraint, that the electric and magnetic fields are perpendicular to the velocity vector $\vec{v}$ of the particle beam: $\vec{v} \cdot \vec{B} = \vec{v} \cdot \vec{E} = 0$.

The gyromagnetic anomaly G , magnetic and electric dipole moments are given by:

$$G = \frac{g-2}{2}, \vec{\mu} = 2(G+1) \frac{eh}{2mc} \vec{S}, \text{ and } \vec{d} = \eta \frac{eh}{2mc} \vec{S}. \quad (3)$$

Methods

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

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1. Frozen spin method [6], 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 precess 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.

For pure electric bending fields (i.e. $\vec{B}=0$) with the additional condition that $\left(G - \frac{1}{\gamma^2 - 1}\right)$, equation 2 simplifies to

$$\frac{d\vec{S}}{dt} = \frac{e\hbar}{2mc} \eta (\vec{E} \times \vec{S}). \quad (4)$$

The above condition can only be fulfilled for a positive gyromagnetic anomaly $G > 0$ (i.e. for a proton) and a fixed particle momentum given by:

$$\gamma = \sqrt{\frac{1}{G} + 1} \Leftrightarrow p_{\text{magic}} = \frac{m}{\sqrt{G}}. \quad (5)$$

For protons a magic momentum of roughly $p_{\text{magic}} = 0.7 \text{ GeV}/c$ has to be chosen to freeze the spin in a pure electric bending field.

In a storage ring with combined electrostatic and magnetic bending fields the following condition has to be fulfilled to freeze the spin motion:

$$G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right) (\vec{v} \times \vec{E}) = 0 \quad (6)$$

In this case the radial E-field cancels the (g-2) spin precession in the vertical B-field, if:

$$E = \frac{GBv\gamma^2}{1 - G\beta^2\gamma^2} \approx GBv\gamma^2, \quad (7)$$

with the approximation that the denominator in equation (7) is close to one. Freezing the spin in a storage ring with combined electric and magnetic bending fields is possible for all particles with both positive and negative gyromagnetic anomaly at any beam momentum.

Two collaborations, one located in the USA (srEDM-US) and the other one in Germany (JEDI, Jülich Electric Dipole moment Investigations), have put forward proposals for dedicated storage ring EDM (srEDM) experiments [3,4]. The aim is to advance the sensitivity level for EDMs of hadronic particles like the proton, deuteron, and ^3He nuclei to $10^{-29} e\cdot\text{cm}$, utilizing the frozen spin method. The srEDM-US collaboration at BNL has proposed an all electric storage ring for protons, while the

newly founded JEDI collaboration at FZJ is pursuing an approach to perform EDM measurements of proton, deuteron, and ^3He ions in one and the same storage ring with combined electric-magnetic deflectors [7].

2. Resonant method [8], were an RF-E/B spin flipper runs at a frequency tuned to the spin tune ($\gamma \cdot G \pm K$, K integer). The transverse electric field of the spin flipper would rotate the spin of stored particles away from the vertical or horizontal spin axis, building up a polarization perpendicular to the original spin direction, depending on the magnitude of the EDM.

As a first step towards EDM searches in storage rings, the JEDI collaboration has submitted a proposal [2] to study the proton and deuteron EDM with an intermediate goal of $10^{-24} e\cdot\text{cm}$ applying the resonance method [9]. It will use the existing but upgraded Cooler Synchrotron COSY, with the addition of RF-E or RF-E/B fields to enhance the EDM sensitivity. This would be the first EDM measurement in the world of a dedicated EDM storage ring experiment.

FIRST DIRECT EDM MEASUREMENT AT THE COOLER SYNCHROTRON COSY

The EDM signal would be a polarization component perpendicular to the original spin direction of the stored particles produced by the EDM-induced precession of the spin in a radio-frequency spin flipper with transverse electric field [9]. With accessible electric field gradients in the MV/m range, the spin will be tipped by a minuscule angle $10^{-13} - 10^{-12}$ rad per single pass and the buildup of an observable polarization in the percent range demands a spin coherence during $10^{10} - 10^{11}$ revolutions of the stored beam, which requires a coherent buildup of polarization for an extremely long time scales of $10^4 - 10^5$ s. Coherent betatron oscillations induced by the transverse electric RF spin flipper field will lead to uncontrolled systematic rotations of the spin.

To suppress perturbations of the particle trajectory induced by the transverse electric RF spin flipper field, RF-E/B fields can be adjusted according to the “Wien-filter” condition: $\vec{E} + \vec{v} \times \vec{B} = 0$. Since $\vec{E}^* = 0$ for the reference particle, there will be no direct EDM effect induced by the RF spin flipper. The spin precession will still be perturbed in the RF-E/B spin flipper via the magnetic moment ($\vec{B}^* \neq 0$) in such way, that the symmetry between spins components parallel and anti-parallel along the momentum vector is broken. If this so called “magic RF Wien-filter” is operated at a resonance frequency of spin motion an EDM effect can be accumulated in the main magnets along the ring.

The different measures towards a first direct EDM measurement contain preparatory measurements at COSY, development of simulation tools and a dedicated hardware:

1. Experimental and theoretical studies of the spin coherence time,
2. investigation of systematic effects,
3. development of precision simulation programs for spin dynamics in storage rings,
4. development of a full-scale polarimeter,
5. and development of a high-power RF-E/B spin flipper system capable to operate at electric fields with more than 1 MV/m with a B-field of roughly 70 G in a frequency range of 0.1 to 1 MHz.

These measures are essential to perform a first direct EDM measurement of proton and deuteron at COSY with a statistical sensitivity of about 10^{-24} e-cm. They will be partially outlined below with an emphasis on the first two items.

Experimental and Theoretical Studies of the Spin Coherence Time

In a storage ring spin decoherence is caused by spin tune spread due to the momentum spread of the beam and spin kicks induced by nonlinear fields.

An important finding from the Jülich EDM Study Group is, that the phase of a particle entering the RF cavity and the phase of the RF spin flipper field are strongly connected to each other, making possible a mutual cancelation spin decoherence for properly chosen beam energies and RF spin flipper harmonics [9]. This prediction needs to be experimentally tested at COSY. An enhancement of the spin coherence time can also be achieved in COSY by operating the RF spin flipper in a special flattop mode. The possibility that operating an RF spin flipper might suppress spin decoherence induced by spin tune spread of stored particles would be an entirely new observation. A search for these decoherence-free energies has never been performed before and would have a strong impact on the whole EDM program.

The spin coherence time of the idle precession (without RF spin flipper on) will limit the observable spin coherence time with spin flipper on. To perform these studies the spin coherence time without RF spin flipper has to be optimized first by means of a phase-space cooling and multipole correction. First results are obtained from a recent experiment conducted at COSY in early 2011 [10]. The analysis of the experimental data is in progress and the preliminary data suggest spin coherence times for deuterons of larger than several hundred seconds.

Investigations of Systematic Effects Studies with RF Spin Flipper

Main sources of systematic errors are the alignment of the RF spin flipper fields with respect to the invariant spin field, opening angle of spin ensemble, field quality (fringe fields) of the RF-E/B spin flipper.

First the alignment angle of the RF spin flipper will be modified to investigate and suppress false spin rotations. After that beam cooling and heating will be applied to change the opening angle of the spin ensemble.

Investigations for a Required COSY Upgrade

It is obvious that a substantial improvement of COSY is required in order to reach the desired EDM sensitivity. False spin rotations as a function of closed-orbit excitation, quadrupole alignment and ring impedances will be studied. The aim of this part is to reduce systematic errors. The results will be the bases to specify the required COSY upgrade (orbit correction system, beam-position monitors (BPMs), power supply stability, magnet alignment and ring impedances):

- An improved closed-orbit control system for orbit correction in the micrometer range is necessary, which requires increasing the stability of correction-dipole power supplies by at least one order in magnitude. The number of correction dipoles and BPMs has to be increased significantly, since the orbit has to be controlled along the entire path length of the beam in the COSY.

- The BPM accuracy, presently limited by electronic offset and amplifier linearity, has to be substantially improved as well. Systematic errors of the closed-orbit measurement (e.g., temperature drift, beam current dependence) have to be studied in detail. In particular, a precise adjustment of the quadrupole and sextupole magnets is mandatory, and the BPMs have to be aligned with respect to the magnetic axis of these magnets. The geodetic alignment of COSY magnets has to be verified. Compensation of phase space coupling and multipole correction to high accuracy is absolutely crucial. Methods of orbit-response matrix, local orbit bumps, turn-by-turn orbit measurements, and beam-based orbit alignment have to be applied to significantly increase the precision of orbit control and knowledge of machine imperfections.

- Beam oscillations can be excited by vibrations of magnetic fields induced by the jitter of power supplies. Investigations have to be carried out with the aim to understand and suppress these beam oscillations to a sufficiently low level, where they do not interfere anymore with the design EDM sensitivity goal.

- The interaction of the circulating beam with the surrounding vacuum chamber produces longitudinal and transverse wake fields, which can lead to transverse and longitudinal beam kicks and excite instabilities. The main sources of wake fields are generally RF cavities and kickers, finite conductivity of wall material, discontinuities of the chamber geometry due to transitions, bellows and beam-position monitors. Transitions of the vacuum chamber profile can have a large impact on transverse and longitudinal beam motion. An accurate estimation of the total impedance budget of the COSY machine has to be carried out. Depending on the outcome, those sections in conflict with the sensitivity goal will be modified.

Table 1: Development Steps of the JEDI Project

Step	Aim / scientific goal	Device / Tools	Storage ring
1	Spin coherence time studies	Low-power RF-B/E spin flipper	COSY
	Systematic error studies	Low-power RF-B/E spin flipper	COSY
2	COSY upgrade	Orbit control, magnets, ...	COSY
	First direct EDM measurement at 10^{-24} e·cm	High-power RF-E/B spin flipper	Modified COSY
3	Built a dedicated all-in-one ring for p, d, ^3He	Common magnetic-electrostatic deflectors R&D funded by ARD (Accelerator Research and Development) of HGF	Dedicated storage ring
4	EDM measurement for p, d, ^3He at 10^{-29} e·cm	Data analysis, systematic error simulation and estimates	Dedicated storage ring

Overall Schedule of the JEDI Project

The stepwise approach of the JEDI Project, starting with the R&D work at COSY, the first direct measurement of a charged particle EDM at COSY, and the design of a dedicated storage ring is summarized in Table 1. The studies of spin coherence time and systematic studies will be performed with a low-power RF-E/B spin flipper with an electric field gradient of tenth of MV/m. For the first direct EDM measurement with a sensitivity goal of at 10^{-24} e·cm a high-power RF-E/B spin flipper is required with an electric field gradient of more than 1 MV/m.

For this first two development steps a timeline of more than five years is estimated. For the next two development steps, that finally lead to the construction of a dedicated EDM storage ring to reach ultimate sensitivity goal of 10^{-29} e·cm, at least another five years have to be projected.

DEVELOPMENT OF PRECISION SIMULATION PROGRAMS FOR SPIN DYNAMICS

Existing spin tracking programs have to be extended to properly simulate spin motion in presence of an electric dipole moment. The appropriate EDM kicks and electric field elements (static and RF) have to be implemented and benchmarked. Furthermore, a symplectic description of fringe fields, field errors, and misalignments of magnets has to be adapted and verified.

One urgently needs spin tracking tools capable of handling up to 10^{11} particle revolutions with highest precision in a realistically modeled storage ring and for large samples of particles. The main challenge for spin tracking including EDM induced spin rotations is the fact that the spin will only be tipped by a minuscule angle due to the EDM of the particle. In the finale dedicated storage ring the EDM rotates the spin by roughly 10^{-9} radians per turn. Assuming a ring structure which contains roughly

hundred elements, the EDM rotates the spin by an angle of approximately 10^{-18} radians per element on average. Thus, a simulation program based on double precision numbers has a very serious limitation to reach the required precision. With a mantissa length of 52 bits roughly sixteen significant decimal digits can only be provided.

Full spin-tracking simulations of the entire experiment are absolutely crucial to explore in a systematic way the feasibility to reach the desired spin coherence time of 10^4 – 10^5 s. Even if the required spin coherence times are achievable, one needs to check whether systematic errors do not limit the anticipated sensitivity to EDMs. In order to provide the required CPU time for the simulations of spin motion with a time scale larger than tens of seconds, spin tracking programs have to be migrated to powerful computer systems or clusters.

Given the complexity of the task, and in order to ensure the credibility of the results, at least two generic simulation programs using different approaches must be developed and benchmarked with the required accuracy and efficiency:

- COSY Infinity [5], based on map generation using differential algebra and the subsequent calculation of the spin-orbital motion for an arbitrary particle. COSY Infinity and its updates are used including higher-order nonlinearities, normal form analysis, and symplectic tracking [11,12]. The upgrade of COSY Infinity will be supervised by M. Berz, the principal developer of the presently available version of this powerful tracking tool. An MPI version of COSY Infinity is already running on the computer cluster at Michigan State University. A project for the Jülich supercomputer is starting in November 2012.
- Integrating program [12], where differential equations of particle and spin motion in electric and magnetic fields are solved using Runge-Kutta integration [13].

They have been shown to be accurate to sub-part per billion levels in describing the muon ($g-2$) spin precession frequency. The integration step size is 0.5 ps, making it rather slow with a possible maximum tracking time of about 10 ms for a particle in the ring. This simulation programs are suitable to study effects that do not require a long numerical time.

The integrating method, even though it is slow, is used for benchmarking the results of the much more efficient COSY Infinity [14]. In addition, numerical integration of the Thomas -BMT differential equations for a spin motion with smoothly approximated parameters of orbital motion can be used to benchmark all simulation programs.

Finally, benchmarking experiments will be performed at COSY to check and to further improve the simulation tools.

CONCLUSION/OUTLOOK

Dedicated storage ring EDM experiments promise to reach a sensitivity level of 10^{-29} e·cm for charged hadronic EDMs. The two collaborations, srEDM-US and JEDI, are pursuing complementary approaches to perform EDM measurements in dedicated storage rings. As an intermediate step, a first direct EDM measurement of protons and deuterons at 10^{-24} e·cm sensitivity level will be carried out in the Cooler Synchrotron COSY.

Full spin-tracking simulations of the entire experiment are absolutely crucial to explore the feasibility of the planned storage ring EDM experiments and to investigate systematic limitations. For a detailed study of particle and spin dynamics during the storage and buildup of the EDM signal, one needs to track a large sample of particles for billion of turns. Existing spin tracking programs like COSY Infinity have to be extended to properly simulate spin motion in presence of an electric dipole moment. In order to provide the required CPU time for the simulations of spin motion with a time scale larger than tens of seconds, spin tracking programs have to be migrated to powerful computer systems or clusters. At least two generic simulation programs using different approaches must be developed and benchmarked with the required accuracy and efficiency. In addition, benchmarking experiments will be 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 spin motion.

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