STUDY OF SYSTEMATIC EFFECTS MIMICKING EDM SIGNAL COMBINING MEASUREMENTS FROM COUNTER-ROTATING BEAMS

V. Cilento*, C. Carli, CERN, Geneva, Switzerland

Abstract

Optimization and realistic estimates of the sensitivity of the measurement of charged particle Electric Dipole Moment (EDM) in storage rings require a good understanding of systematic errors that can contribute to a vertical spin build-up mimicking the EDM signal to be detected. A specific case of systematic effects due to offsets of electrostatic bendings and longitudinal magnetic fields is studied. Spin tracking simulations to investigate whether this special case generates spin rotations, which cannot be disentangled from the ones due a finite EDM by combining observations made with both counter-rotating beams as predicted by analytical derivations, will be presented.

INTRODUCTION

Several schemes to measure the Electric Dipole Moment (EDM) of charged particles are discussed at present. Most of these proposals foresee to run a synchrotron satisfying the frozen spin condition. This condition requires that, in the absence of an EDM and with the well-known Magnetic Dipole Moment (MDM) in a perfect machine, bunches with initial longitudinal polarization (parallel or antiparallel to the direction of movement) remain longitudinally polarized. The effect of a finite EDM is a rotation of the spin from the longitudinal direction into the vertical one. The resulting vertical spin build up, which is very small for the smallest EDM to be detected in typical proposals, is measured with a polarimeter [1].

Systematic effects are any phenomena other than an EDM generating a vertical component of the polarization and limit the sensitivity, i.e. the smallest detectable EDM, of the proposed experiment. Such systematic effects may be generated by unwanted electric fields owing to imperfections in the focusing structure, such as misalignments of components, by magnetic fields penetrating the magnetic shielding or generated inside the shield (for example by the beam itself or the RF cavity), or gravity [2]. A combination of several such phenomena or a combination of an average horizontal polarization and one of these phenomena may also lead to such systematic effects. This paper describes a special case of systematic effects limiting the sensitivity of the experiment caused by transverse offsets of electrostatic bending elements and residual longitudinal magnetic fields inside the magnetic shieldings. The effect occurs both in purely electrostatic EDM rings and in hybrid rings with magnetic focusing. Simulations have been carried out for the symmetric hybrid ring proposal [3].

In most proposals (see, e.g., Refs. [2–4]), a target sensitivity of 10^{-29} $e{\cdot}$cm is quoted, that corresponds to a vertical spin precession rate of 1 nrad/s for the 800 m circumference symmetric hybrid ring (this number will be useful throughout the work). Thus, any non EDM originating vertical spin precession rate larger than 1 nrad/s is considered a potential systematic error source.

We can distinguish between first order systematic effects and second order ones. First order effects, where one machine imperfection contributes to a vertical spin build up and second order effects, where instead two machine imperfections contribute to a vertical spin build up. In this paper, we will focus on a specific case of a second order effect, a geometric phase effect, due to horizontal offsets of bends and longitudinal magnetic fields penetrating the shield, described in Fig. 1. In this specific case we will have two machine imperfections. The horizontal offsets of bends will generate spin rotation in the horizontal plane due to the fact that the particle is no more at the magic energy while the longitudinal magnetic fields rotate the spin around the longitudinal axis generating a small vertical spin component. The fact that rotations are not commutative leads to a rotation around the radial axis, i.e., a typical geometric phase effect. Moreover, betatron oscillations are neglected with the analysis restricted to particles following the closed orbit.

GEOMETRIC PHASE EFFECT DUE TO OFFSET OF BENDS AND LONGITUDINAL MAGNETIC FIELDS

This study includes BMAD [5] implementation of the symmetric hybrid ring lattice proposal and the study of a second order systematic effect: the geometric phase effect due to offset of bends and longitudinal magnetic fields. The symmetric hybrid ring design has been chosen for this study because it has interesting features, as the absence of spin rotation proportional to the unwanted magnetic fields due to focusing using magnetic quadrupoles. Anyway, it is necessary to take into consideration that, for this specific ring, the lattice is different for counter-rotating beams and thus the tuning is more delicate. More details on this lattice proposal can be found in Ref. [3].

Simulation Results for a Simplified Case

A simplified case studied here to understand the effect is generated by two bending offsets by ±10 mm interleaved in two locations with longitudinal magnetic fields (integrated fields of 0 nTm, ± 1 nTm, ± 10 nTm and ± 100 nTm). The strength of the bendings is adjusted such that the deflection (corresponding, e.g., to a slight change of the electrode spacing) vanishes. In practice, independent positioning and strength errors will occur and generate orbit distortions resulting in additional systematic effects to be taken into ac-

---

* vera.cilento@cern.ch

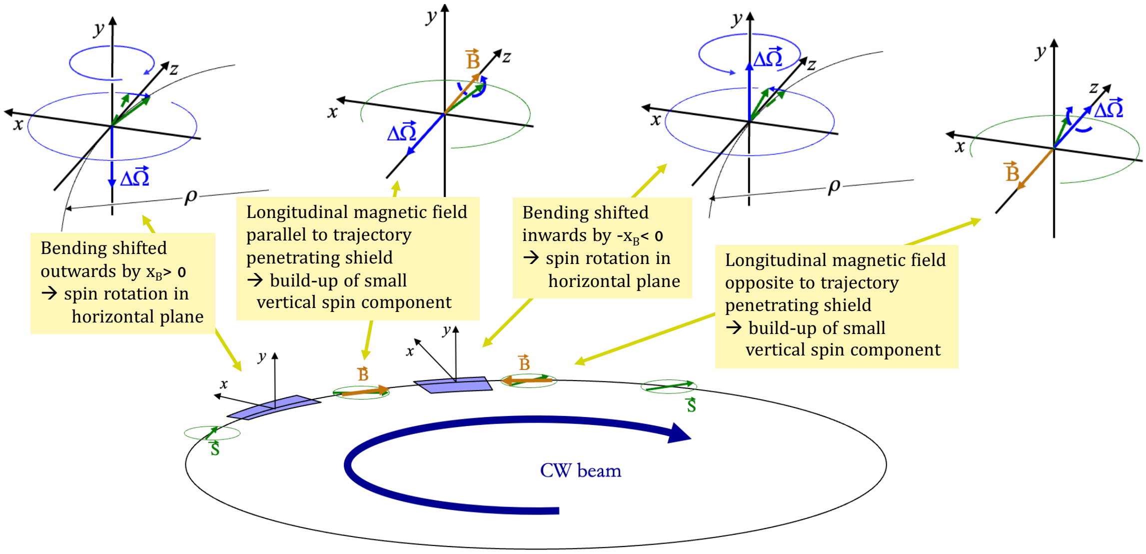

Figure 1: Detailed description of the mechanism of the geometric phase effect described in this paper.

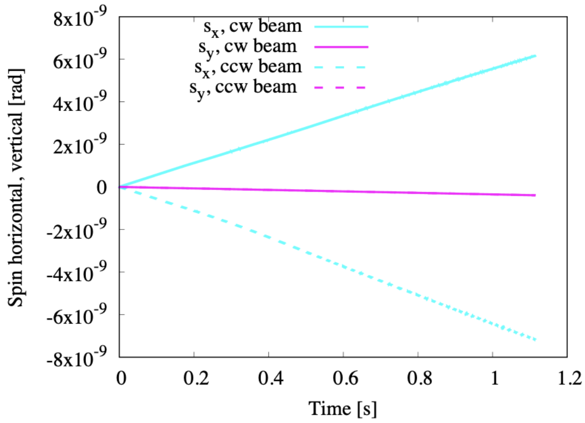

Figure 2: Horizontal and vertical spin build up for the CW and CCW beams with only the horizontal offsets of bends and no longitudinal magnetic fields.

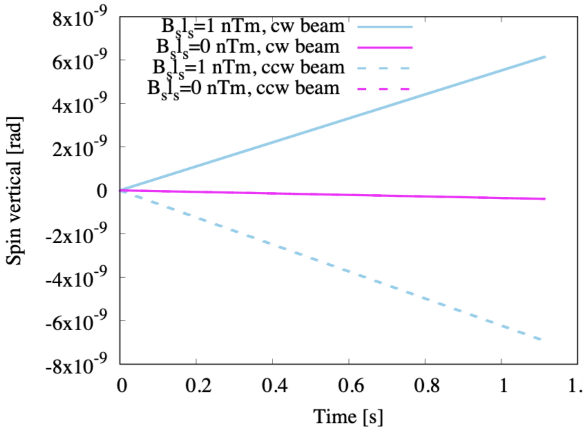

Figure 3: Vertical spin build up for the CW and CCW beams without longitudinal magnetic fields and with longitudinal magnetic fields of 1 nTm.

count for a realistic sensitivity estimate. The effect is independent on the location of the machine imperfections provided bending offsets and longitudinal magnetic fields are interleaved. For the simulation presented here, all imperfections are located within a small portion of the ring. Simulations have been carried out for clockwise (CW) and counter-clockwise (CCW) beams showing that, as expected, the effect cannot be disentangled from a finite EDM. After implementing the bending offsets and without longitudinal magnetic fields, the particle energy has been slightly adjusted to reduce a slow spin rotation in the horizontal plane resulting in the spin evolution plotted in Fig. 2 for a proton initially polarized in longitudinal direction. The effect of adding weak integrated longitudinal magnet fields of ± 1 nT is shown in Fig. 3. Transverse spin components for a proton with initially longitudinal polarization for different additional integrated longitudinal magnetic fields in plotted in Figs. 4 and 5. One notes that the residual radial spin component after readjusting the particle energy is independent of the additional longitudinal magnetic fields. From Fig. 5, one observes that the vertical spin component generated by the effects agrees well with with analytical estimates and is as expected proportional to the additional longitudinal magnetic fields.

Simulation Results for a More Realistic Case

To understand the real limitation that can have this effect on the EDM measurement, a more realistic case has been studied. This involves a random offset of all the bendings with a reasonable small radial misalignment of 0.1 mm rms and reasonable longitudinal magnetic fields added with 48 solenoids with a length of 1 m and a random rms $k_S = B_s/B\rho$ value of 10^{-9} m^{-1}. In addition, the field of the bendings has again been adjusted (electrode spacing) to have no (or negligible) orbit deformation. Then, simulations have been done without any further correction and after adjusting the

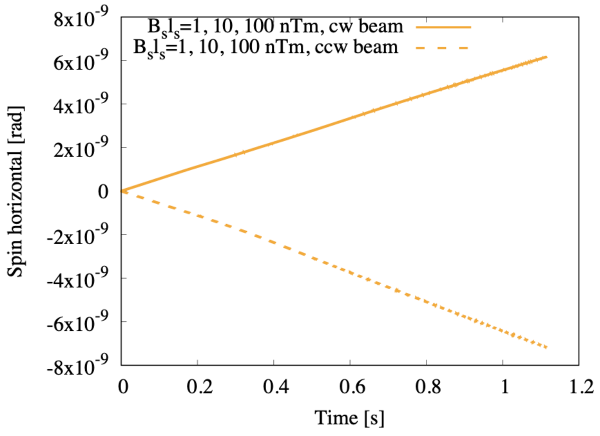

Figure 4: Horizontal spin build up for the CW and CCW beams with longitudinal magnetic fields of 1, 10, 100 nTm.

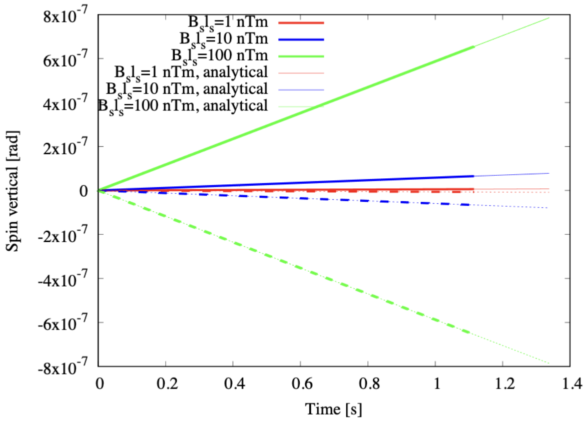

Figure 5: Vertical spin build up and comparison with analytical estimates for the CW and CCW beams with longitudinal magnetic fields of 1, 10, 100 nTm.

beam energy to strongly reduce a rotation in the horizontal plane and then setting the integrated longitudinal field to zero. The results are shown for a longitudinally polarized beam and in addition different random seeds have been used for comparison (case 1 and case 2 in Figs. 6 and 7). Figure 6 shows the horizontal spin build up before and after applying the energy correction. In fact, by applying the correction we can see that the horizontal spin build up goes very close to zero as we expect (the blue lines). Figure 7 shows instead the vertical spin build up before and after applying the longitudinal magnetic field corrections (set the integral over one turn to zero). In fact, by doing that we can see that the effect from quadratic becomes linear as expected and it is equal to ≈ 3 nrad/s.

CONCLUSION

Geometric phase effects caused by offsets of bendings and residual longitudinal magnetic fields inside the shield have been studied. The offset of the bendings generate spin rotation in horizontal plane while the longitudinal magnetic fields generate rotations around longitudinal axis. The net

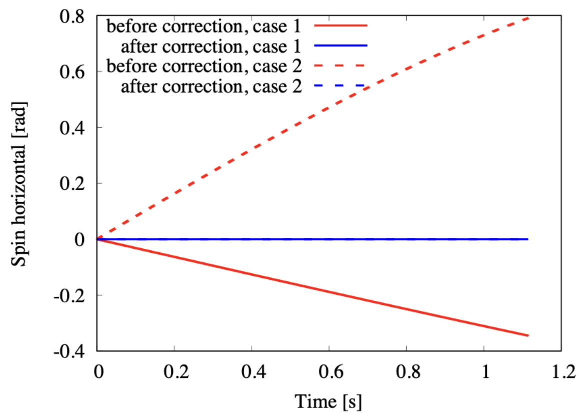

Figure 6: Horizontal spin build up before and after applying the energy correction for two different random seeds.

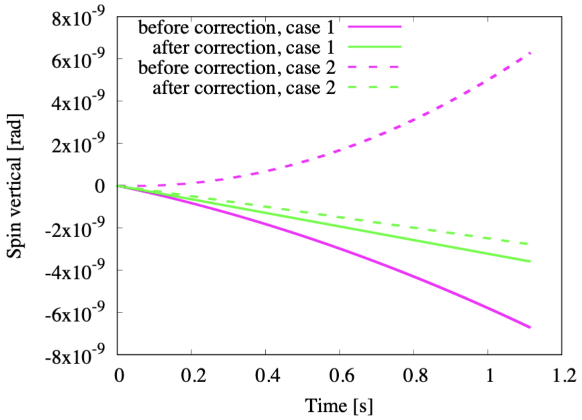

Figure 7: Vertical spin build up before and after applying the energy and the longitudinal magnetic field correction for two different random seeds.

effect is a rotation around the radial axis that rotates the longitudinal spin component into the vertical direction. It has been shown that this effect mimics a finite EDM (cannot be disentangled from EDM combining observations with CW and CCW beams). From the simulations for the more realistic case, possibly with still optimistic assumptions, for a longitudinally polarized beam there is a geometric phase effect of ≈ 3 nrad/s, 3 times larger than what an EDM of 10^{-29} e·cm would give. Moreover, the orbits of the counter-rotating beams do not separate. The effect occurs for any frozen spin machine and not only the symmetric hybrid lattice [3] used for simulations. This is an example of a geometric phase effect that cannot be disentangled from a finite EDM by combining spin rotations made with both counter-rotating beams.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Physics Beyond Colliders Study Group and the CPEDM collaboration for the support of the work and in particular, the srEDM team for the helpful discussion.

REFERENCES

[1] C. Carli and M. H. Tahar, “Geometric phase effect study in electric dipole moment rings”, *Phys. Rev. Accel. Beams*, vol. 25, p. 064001, 2022. `doi:10.1103/PhysRevAccelBeams.25.064001`

[2] F. Abusaif *et al.*, “Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study”, CERN, Geneva, Switzerland, CERN-PBC-REPORT-2019-002. `doi:10.48550/arXiv:1912.07881`

[3] Z. Omarov *et al.*, Comprehensive Symmetric-Hybrid ring design for pEDM experiment at below $10^{-29} e\cdot$cm, 2020. `doi:10.48550/arXiv.2007.10332`

[4] Storage Ring EDM Collaboration, “A proposal to measure the proton electric dipole moment with $10^{-29} e\cdot$cm sensitivity”, 2011. `https://inspirehep.net/literature/1865072`

[5] BMAD: Software Toolkit for Charged-Particle and X-Ray Simulations, `https://www.classe.cornell.edu/bmad`