STATISTICAL PRECISION ESTIMATION IN CHARGED PARTICLE EDM SEARCH IN STORAGE RINGS

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Abstract

Currently, the "Jülich Electric Dipole moment Investigations" (JEDI) collaboration together with the present EDM experiments on the COSY ring is developing the conceptual design of a ring specifically for the search for the deuteron electrical dipole moment (dEDM). One of the main problems in the EDM study is the spin precession in the vertical plane caused by the non-ideal positioning of the accelerator elements through the magnetic dipole moment (MDM). The idea of how to separate the EDM from MDM is based on measuring the spin tune in different processes and comparing the results. The high precision of the spin tune measurement is achieved by collecting data during one year. The JEDI collaboration aims detecting the dEDM at a level better than $<10^{-29}$, which one requires precision in the frequency estimate $\sim 10^{-9}$. An estimate's statistical precision is conditional on the following factors: the total measurement time, determining the independent variable spread; measurement error; temporal modulation and spacing of sample points.

In this paper we analyze the interplay between these factors, and estimate the best achievable precision under the given conditions.

INTRODUCTION

One of the essential problems of modern physics is the baryon asymmetry of the Universe that represents the prevalence of matter over antimatter [1]. In addition, cosmic detectors, whose purpose is to search for antimatter, PAMELA and AMS haven't found any significant amount of it in the Universe yet [2]. The development of the new idea that claims one of the reasons for the baryon asymmetry is the breaking of CP invariance, has begun soon after its discovery. A. Sakharov established three necessary conditions for baryogenesis (initial creation of baryons) in 1967 [3]:

- Baryon number violation;
- C-symmetry and CP-symmetry violation;
- Interactions out of thermal equilibrium.

Many theories beyond the SM have been proposed and all of them of so-called "New Physics" are able to remove the difficulties that one meets in the Standard Model, but their experimental confirmation has yet to be found. One of the possible arguments for the breaking of CP-invariance is the existence of non-vanishing electric dipole moments (EDM) of elementary particles.

Currently, the "**J**ülich **E**lectric **D**ipole Moment **I**nvestigation" (JEDI) collaboration works in two directions: first on the existing accelerator COSY the precursor experiment is carried out to prove the feasibility of EDM measurement using the storage ring [4,5,6], and secondly the conceptual design of the ring specifically for search of the deuteron electrical dipole moment (dEDM) is being developed [7]. At present the RF flipper for installation on COSY ring is progressing successfully. Besides, we have already obtained very important experimental results with precise measurements of the spin precession frequency [4,5] which will allow calibrating the particle energy using the clock-wise and counter clock-wise procedure, and we have reached the longest spin coherence time ~1000 sec in horizontal plane [6].

BASIC PRINCIPLE OF EDM SEARCH IN RING

At present there are two options of future dEDM ring based on the frozen (FS) and quasi-frozen spin (QFS) concepts [7]. The idea of FS concept has been suggested by BNL [8], and it is based on the elements with incorporated electric and magnetic fields in one element, when the spin of the reference particle is always orientated along the momentum.

Studying the FS structure, we have paid attention to the fact that the frozen spin condition is performed only for the reference particle, and the spin vector of all other particles oscillates relative the frozen direction. But if so, it might not be worth it to strictly fulfill the frozen spin condition even for the reference particle. Let us see if the spin oscillates in the horizontal plane with respect to the frozen spin direction with amplitude Φ_s, then the EDM growth decreases proportionally to the factor $J_0(\Phi_s) \approx 1-(\Phi_s)^2/4$. Taking into account that the deuteron's anomalous magnetic moment $G = -0.142$ has a small value and the fact that the spin oscillates around the momentum direction within half value of the advanced spin phase $\pi \cdot \gamma G/2$ in the magnetic arc, each time returning in the elements with electrical field on the straight sections, it is obvious that the effective contribution to the expected EDM effect is reduced only by a few percent. This allows us to proceed to the concept of quasi-frozen spin QFS [9], where the spin is not frozen with respect to the momentum vector, but continually oscillates around momentum with small amplitude of few degrees.

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In case of the quasi-frozen spin concept, we have two options of lattice. In the first option, the electrical and magnetic fields are fully spatially separated in arcs and straight section elements.

In second option of QFS lattice we introduced a magnetic field of small value ~100 mT, compensating the Lorentz force of the electric field on straight section (see fig.1).

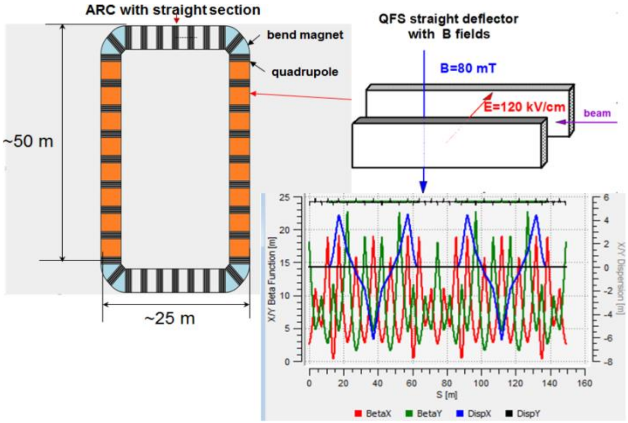

Figure 1: QFS lattice with TWISS functions.

In both cases the QFS lattice has the conventional magnetic arcs with the zero dispersion on the straight sections in the middle for installation of the polarimeter, the beam extraction and injection systems, and the RF cavity.

The QFS concept simplifies the EDM lattice and makes it possible to realize QFS concept in existing COSY ring to search for dEDM.

SYSTEMATIC ERRORS

Generally, the measurement errors can be divided into two components: random errors and systematic errors. The systematic error is called the error component, which remains constant in repeated measurements and is caused by imperfections of the physical facility. In the EDM ring experiment, the systematic error arises due to the misalignments of electric and magnetic elements in the ring and causes a "fake" EDM signal. The nature of origin being random errors, the misalignments create conditions for systematic errors in EDM experiments. The installation errors (misalignments) are associated with limited capabilities of the geodetic instruments. As is known, the bending magnet (or the electric deflector) can be rotated in three planes. We consider only the rotation around the longitudinal and transverse axis, because the rotation around the vertical axis does not introduce a systematic error.

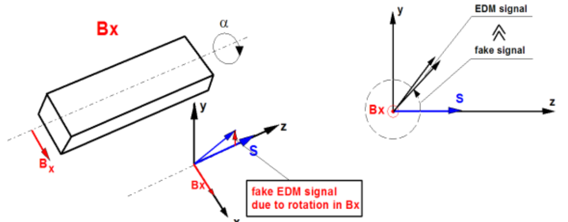

Figure 2: Magnet rotating relative to longitudinal axis.

First, let us consider the case of the magnet rotated relative to the longitudinal axis (see Fig.2). Due to such rotation, a horizontal component of the magnetic field B_x arises and causes the spin rotation $\Omega_x = \Omega_{\mathrm{Bx}}$ in the same plane where we expect the EDM rotation. To illustrate, let us write the solutions of T-BMT equations with initial condition $S_x = 0,\ S_y = 0,\ S_z = 1, \Omega_z = 0$ and $\Omega_x \neq 0$ in simplest form:

$$S_x(t) = \frac{\Omega_y \sin(\sqrt{\Omega_x^2 + \Omega_y^2}\, t)}{\sqrt{\Omega_x^2 + \Omega_y^2}}; S_y(t) = -\frac{\Omega_x \sin(\sqrt{\Omega_x^2 + \Omega_y^2}\, t)}{\sqrt{\Omega_x^2 + \Omega_y^2}}. \quad (1)$$

Taking into account the above, we can present components: $\Omega_x = \Omega_{EDM} + \Omega_{\mathrm{Bx}}$ and $\Omega_y = 0 + \delta\Omega_{\mathrm{decoh}}$, where Ω_{EDM} is the frequency of spin rotation due to the presence of an EDM, B_x is the horizontal component induced by the magnet rotation (misalignments), and $\delta\Omega_{\mathrm{decoh}}$ is the spin tune decoherence in the horizontal plane. Since the decoherence is allowed to reach an rms value of 1 rad for spin coherence time t_{SCT}>1000 sec, that is the rms value of $\langle \delta\Omega_{\mathrm{decoh}} \rangle \approx 10^{-3}$ rad/sec.

The magnets are supposed to be installed at the technically realized accuracy of 10μm, which corresponds to the rotation angle of the magnet around the axis of about $\alpha_{\max} = \pm 10^{-5}$ rad. Using COSY Infinity [10] and MODE [11], we have calculated the MDM spin rotation due to B_x, which is $\Omega_{Bx} \approx 3$ rad/sec. At the same time, at presumable EDM value of $10^{-29}\, e\cdot\mathrm{cm}$, the EDM rotation should be $\Omega_{EDM} = 10^{-9}$ rad/sec, that is $\Omega_{EDM}/\Omega_{Bx} \approx 10^{-9}$, and the expression (1) can be simplified without loss of measurement accuracy of possible signal EDM at the level of 10^{-9}:

$$\langle S_x(t) \rangle = \frac{\langle \delta\Omega_{decoh} \rangle}{\Omega_{Bx}} \sin\Omega_{Bx} t;\ S_y(t) = -\sin(\Omega_{Bx} + \Omega_{EDM})t\,. \quad (2)$$

We can see from the first equation of (2) that the spin decoherence in the horizontal plane is not growing and is stabilized at the level of $\langle S_y \rangle \sim \langle \delta\Omega_{decoh} \rangle / \Omega_{Bx} \approx 10^{-3}$. This is a significant positive feature. But to be fair, we should understand that, since $\Omega_{Bx} = \frac{e}{m\gamma}(\gamma G + 1)B_x$, we will now get due to $\gamma = \gamma_0 + \Delta\gamma$ the spin frequency decoherence $\Omega_{Bx} = \Omega_{x,\gamma=\gamma_0} + \Delta\Omega_{x,\Delta\gamma}$ in the vertical plane around horizontal axis, which one we can minimize by the same methods (sextupoles, RF) as in horizontal plane. In addition, we are really deprived of ability to measure the accumulated EDM signal by growth of the vertical component of spin suggested in [8], since the spin rotation due to the magnet errors is much faster than due to possibly existing EDM $\Omega_{Bx} >> \Omega_{EDM}$. That is S_y reach a maximum for very short time meanwhile the signal EDM does not have time to be accumulated.

Therefore, the only solution is to measure the total frequency $\Omega_{Bx} + \Omega_{EDM}$, but in order to split out the EDM signal from the sum signal, we need an additional condition. Such a condition is to measure the total spin frequency in the experiment with a counter clock-wise (CCW) direction of the beam $\Omega_{CCW} = -\Omega_{Bx}^{CCW} + \Omega_{EDM}$ and compare with clock-wise (CW) measurements $\Omega_{CW} = \Omega_{Bx}^{CW} + \Omega_{EDM}$. Simultaneously, we must understand that the accuracy of the frequency measurement of $\Omega_{CW}, \Omega_{CCW}$ determines the precision of the EDM measurement.

Let us assume that we can measure the spin frequencies $\Omega_{CW}, \Omega_{CCW}$ with accuracy $\Delta\Omega_{CW,CCW}$ =10^{-9}, which will be discussed in details in the next paragraph. Then we will be able to determine the EDM signal by simple addition $\Omega_{EDM} = (\Omega_{CW} + \Omega_{CCW})/2 + (\Omega_{Bx}^{CCW} - \Omega_{Bx}^{CW})/2$ at the level of ~10^{-29}e·cm. The additional orders of magnitude can be obtained by the time modulation of the "diamond pellets" target (frequency of following diamonds) and higher detector rate [13]. It would allow having bigger number of useful events in the interval when the polarization asymmetry changes faster and having the smaller statistic errors. Thus, such an approach looks promising.

However, we need to be sure that when the sign of the driven magnetic field B_y for the CW-CCW is changed, the magnetic field component B_x is restored with the required relative precision of not lower than 10^{-10}. Therefore, we suggest calibrating the field in the magnets using the relation between the beam energy and the spin precession frequency in the horizontal plane, that is, determined by the vertical component B_y. Since the magnet orientation remains unchanged, and the magnets are fed from one power supply, the calibration of B_y will restore the component B_x with the same relative accuracy 10^{-10}, which applies to the difference $\Omega_{Bx}^{CCW} - \Omega_{Bx}^{CW}$ as well. Besides, we should mention that the calibration in the horizontal plane does not involve the EDM signal. Thus, this calibration will not decrease the accuracy of EDM measurement, and it will be finally defined by accuracy of $\Omega_{CW,CCW}$ measurement.

We shall not discuss here the other systematic errors arising from the rotation of the magnet with respect to the longitudinal axis, because it does not mix EDM and MDM signal and is quite well discussed in [12].

STATISTICAL SENSITIVITY OF EDM MEASUREMENT

So,……

CONCLUSION

In the paper, we analyzed the frozen and quasi-frozen spin structures, taking into account the effect of spin decoherence and systematic errors. It has been shown how you can measure the EDM in an imperfect ring using achieved the experimental results of spin tune measurement and the beam polarization lifetime of 1000 sec. In the proposed conception we use: the calibration energy in horizontal plane and measurement in vertical plane, the invariability of ratio B_x to B_y after change of polarity in all elements. These estimates show that the lower limit of detection of presumably existing EDM can be as low as ~10^{-29}e·cm.

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