Optimization of Spin Coherence Time at a Prototype Storage Ring for Electric Dipole Moment Measurements

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The JEDI experiment is devoted to the search for the electric dipole moment (EDM) of charged particles in a storage ring, as a very sensitive probe of physics beyond the Standard Model. In order to reach the highest possible sensitivity, a fundamental parameter to be optimized is the particles' Spin Coherence Time (SCT), i.e., the time interval within which the particles of the stored beam maintain a net polarization greater than 1/e. To identify the working conditions that maximize SCT, accurate spin-dynamics simulations with the code BMAD have been performed on the lattice of a "prototype" storage ring which uses a combination of electric and magnetic fields for bending. This work will present the results of these simulations addressing the impact on the SCT of different factors like horizontal tune, synchrotron tune and effect of the electric bending components.

KEYWORDS: Storage rings; Polarized beams; Spin-coherence time

1. INTRODUCTION

Of all the observable matter antimatter asymmetry in the universe only a small fraction is accounted for by the currently accepted Standard Model (SM). Assuming the CPT theorem to hold true, it appears that this asymmetry can only be explained by additional CP violating processes than those accounted for in the SM [1]. A noticeable manifestation of CP violation is the presence of an Electric Dipole Moment in a proton, whose magnitude can indicate the existence of additional CP violation Beyond the Standard Model (BSM). While the SM predicts an EDM $\leq 10^{-31}\, e.cm$, some supersymmetry theories place it orders of magnitude higher ($\leq 10^{-26}\, e.cm$).

The JEDI collaboration is currently working on performing this measurement using storage rings. EDM can be measured using a storage ring through precise observation of the interaction of particle spin with electric and magnetic fields. Since the EDM will point in the same direction as the spin, the presence of EDM will result in a torque on the particle in response to an electric field. The visible effect of this torque can be magnified using specially configured external electric fields. Since the major challenge in performing such a measurement on a proton is that its EDM would be very small, the measurement would require the construction of a dedicated storage ring [2] [3]. But before building such a ring, its feasibility must be demonstrated. So, to this end the JEDI collaboration will approach this problem in three stages. The first stage involves experiments at the Cooler Synchrotron (COSY) in FZ, Jülich, with only magnetic bending Fields. The second stage involves simulation of spin motion in a prototype storage ring which uses a combination of electric and magnetic bending Fields. Once the feasibility of the prototype has been established, the final stage can be initiated, which would involve the design, simulation, and construction of a purely electric storage ring, which would have the targeted precision to perform the EDM measurement.

2. THE PROTOTYPE EDM RING

2.1. Frozen Spin Condition

Assume a circular storage ring where the magnetic field is uniform, upward, and perpendicular to the ring plane; and the electric field is radially inward, pointing towards the center. The spin motion of a particle in this storage ring is governed by the Thomas-BMT equation [4]:

$$\frac{d\vec{s}}{dt} = \left[\left(\overrightarrow{\Omega_{MDM}} - \overrightarrow{\Omega_{ring}}\right) + \overrightarrow{\Omega_{EDM}}\right] \times \vec{s}$$

Ω_{MDM} and Ω_{EDM} are the angular velocity components due to interaction of the magnetic and electric dipole moments with the bending fields, and Ω_{ring} is the angular velocity of particle's revolution around the ring. Since for a vertical magnetic field, $\overrightarrow{\Omega_{MDM}}$ and $\overrightarrow{\Omega_{ring}}$ are collinear, and…

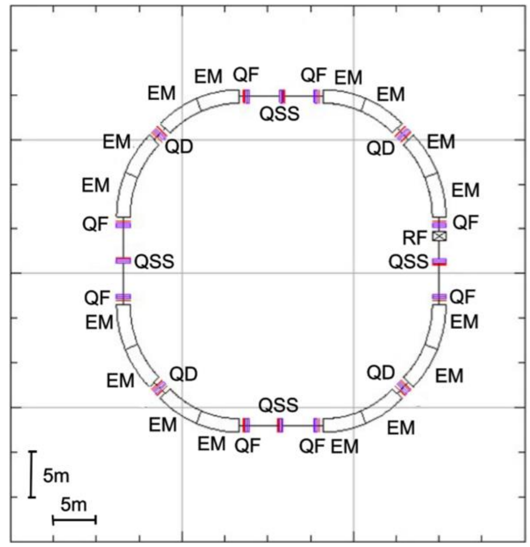

Figure 1: The floor plan of the prototype EDM ring from Tao [7]. Dipoles are labeled with 'EM', quadrupoles corresponding to their family with 'QF', 'QD' or 'QSS' and the cavity with 'RF'.

$$\overrightarrow{\Omega_{MDM}} - \overrightarrow{\Omega_{ring}} = -\frac{q}{m}\left[G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}\right]$$

There exist certain combinations of E, B and γ such that $\overrightarrow{\Omega_{MDM}} - \overrightarrow{\Omega_{ring}}$ vanishes entirely [4]. This is called "frozen spin" since in this configuration, the spin vector is aligned with the particle momentum at all times. Therefore, any torque on the particle is now solely due to the EDM, and will always be vertically upward, causing a gradual buildup of vertical polarization among particles in the ring. The rate of this buildup will be proportional to the magnitude of the particle's EDM.

2.2. Spin Coherence Time

Assuming a bunch of n particles are maintained in the storage ring, let $\hat{s}_i(t)$ be the unit vector in the direction of the i^{th} particle's spin vector. The total spin vector $\vec{S}(t)$ is:

$$\vec{S}(t) = \frac{1}{n}\sum_{i=1}^{n} \hat{s}_i(t)$$

If initially all particle spins are aligned with their momenta ($\left|\vec{S}(0)\right| = 1$), the time t_c taken for $\left|\vec{S}(t_c)\right| = \frac{1}{e}$ is defined as Spin Coherence Time (SCT). This quantity is ideal for evaluation of a storage ring for EDM measurements since very gradual polarization buildups would be noticeable only if the bunch remains spin-coherent. Therefore, longer SCT in a storage ring indicates a higher accuracy in potential EDM measurement.

3. DESIGN

The proposed design [5] [6], shown in Figure 1 consists of four unit-cells, each with two bending dipoles, 4 quadrupoles and 4 sextupoles to provide sufficient flexibility in beam optics. The quadrupoles present on the ring are categorized into three families: QF (2 per unit cell, focussing), QD (1 per unit cell, defocussing) and QSS (1 per unit cell, in the straight section). The sextupoles are placed on the same locations as the quadrupoles and are categorized into similar families: SXF, SXD and SXSS. Each family of magnets have a common power supply for centralized control. During this study however, the SXSS and QSS magnets were turned off. An RF-cavity is also placed at one of the straight sections for bunching (longitudinal focussing) of particles. In the lattice used in this study, $\vec{E}$, $\vec{B}$ and γ values are optimized for a pre-set particle momentum of $294.057\ MeV/c$, a track-length of $123.36\ m$ and a bending radius of $12.248\ m$.

4. PARAMETER SPACE

Given the lattice design described in the previous section, a gaussian bunch of 1000 particles is simulated in BMAD [7] with emittances set to $\epsilon_{x,y} = 5 \times 10^{-7}$. The spin dynamics is now influenced by the two quadrupole and two sextupole field strengths. These fields determine the Betatron tunes Q_x and Q_y, and chromaticities ξ_x and ξ_y [8]. These parameters are organized as shown in Figure 2.

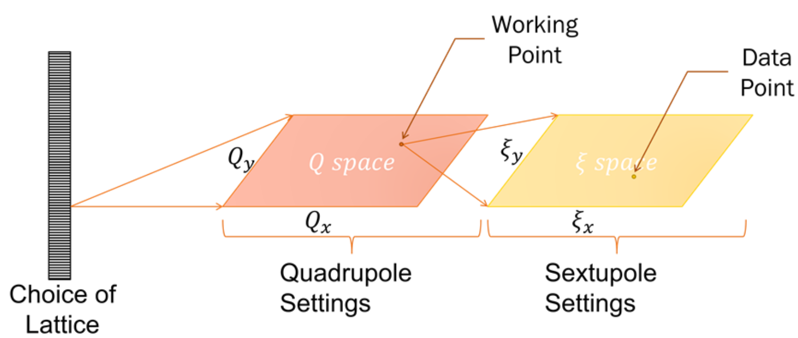

Figure 2: Organization of free parameters in the prototype EDM lattice. Each set of Q_x and Q_y (adjusted by the quadrupole field strengths) is a working point on the Q-space, and each set of ξ_x and ξ_y (adjusted by the sextupole field strengths) is a data point on the ξ-space.

This study aims to find the maximum value of SCT at each working point chosen, and consequently the maximum achievable SCT by the lattice. In addition to this, insights can also be gained on the nature and sensitivity of the influence of various parameters on the SCT.

5. RESULTS

SCT is measured by simulating a bunch of particles travelling around the storage ring and tracking the value of the resultant spin vector $\vec{S}(t)$ over several turns. The data is fitted and extrapolated to its intersection point with $\vec{S}(t) = \frac{1}{e}$. Examples of spin decoherence of 1000 particles is shown in Figure 3.

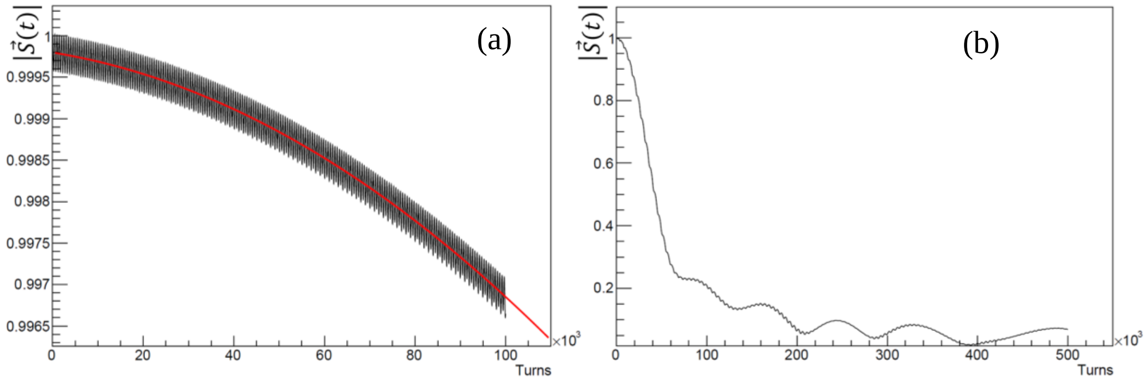

Figure 3: (a) Decoherence of a bunch of particles in the prototype ring at $Q_x = 1.823$, $Q_y = 1.123, \xi_x = 2.0$, $\xi_y = -3.5$ in 10^5 turns, fitted with a 2nd degree polynomial. (b) Decoherence of a bunch of particles with a lower SCT at $Q_x = 1.723$, $Q_y = 1.123, \xi_x = 0.5$, $\xi_y = -5.5$ in 5×10^5 turns, showing the later stages of its decoherence.

Simulations were run on a total of 1224 data points at 17 working points, starting with $\left(Q_x = 1.823,\ Q_y = 1.123\right)$. This point was chosen due to its low natural chromaticity (the chromaticity of the beam measured when the sextupoles are turned off), and so presumed likely to have the highest SCT.

5.1. *Maximum SCT*

Initially, the first working point was explored. Points on the ξ-space were measured for their SCT and plotted as shown in Figure 4. Each working point has an associated ξ-space and a maximum SCT.

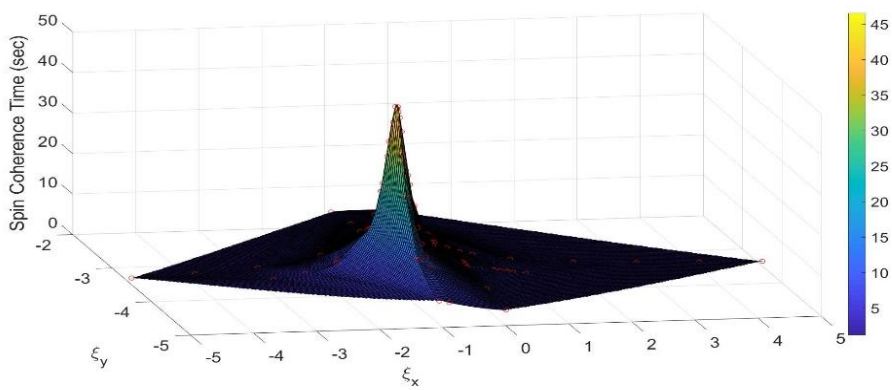

Figure 4: A surface plot of SCT values interpolated from 91 data points at $Q_x = 1.823$, $Q_y = 1.123$.

6. CONCLUSIONS AND FUTURE STUDY

It was initially postulated that the maximum SCT would occur at working points with low natural chromaticities. This however appears not to be the case for the prototype ring. Furthermore, the SCT is highly sensitive to the chromaticity setting (favouring more negative values) as well as horizontal focusing (favouring stronger focusing).

The highest SCT measured so far is $150\ s$ at $Q_x = 1.823, Q_y = 0.823, \xi_x = -1.5$, $\xi_y = -2.4$. Since negative chromaticities correspond to increased path lengths, which can affect transverse focussing [9], high SCTs were achieved through optimization of the two factors.

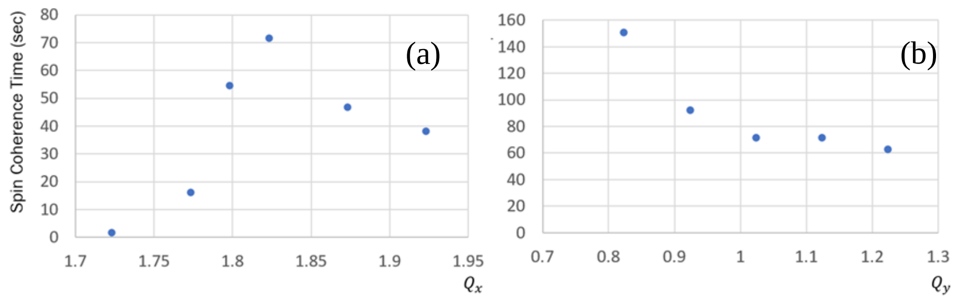

Figure 5: Results of the first two linear scans on the Q-space. In (a), $Q_y = 1.123$. The Q_x value in the first scan with the maximum SCT (1.823) was fixed during the subsequent perpendicular scan shown in (b).

The local oscillations undergone by $\vec{S}(t)$, as can be seen in the decoherence graph in Figure 3, was shown to be correlated with synchrotron oscillations due to the particle acceleration by the RF cavity. However, decoherence is unaffected by RF voltage.

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