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Optimization of spin coherence time at a prototype storage ring for electric dipole moment measurements

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JEDI COLLABORATION

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Summary. — 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 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 the 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.

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 would be 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 $\leq 10^{-31}\,\mathrm{e}\cdot\mathrm{cm}$, some supersymmetry theories place it orders of magnitude higher ($\leq 10^{-26}\,\mathrm{e}\cdot\mathrm{cm}$). The JEDI Collaboration is currently working on performing this measurement using storage rings. An EDM can be measured using a storage ring through precise observation of the interaction of the particle spins with electric and magnetic fields. Since the EDM will point to the same direction as the spin, the presence of an EDM will result in a torque on the particle in response to an electric field. The visible effect of this torque can be

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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. To this end, the JEDI Collaboration is approaching this problem in three stages. The first stage involves experiments at the Cooler Synchrotron (COSY) in FZ, Jülich. The second stage involves a prototype storage ring which uses a combination of electric and magnetic bending fields which are adjusted so that the spin of a reference particle is aligned with its momentum at all times. This is referred to as a "froze-spin" condition. 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, designed to store particles with frozen spin. This ring would have the targeted precision to perform the EDM measurement.

1˙1. *Spin coherence time.* – Considering a bunch of n particles in the storage ring, let $\widehat{s}_i(t)$ be the unit vector in the direction of the i-th particle's spin vector. The total spin vector $\overrightarrow{S}(t) = \frac{1}{n}\sum_{i=1}^{n}\widehat{s}_i(t)$. If initially all the particles spins are aligned with momentum ($|\overrightarrow{S}(0)| = 1$), the time t_c taken for $\overrightarrow{S}$ to reduce to $|\overrightarrow{S}(t_c)| = \frac{1}{e}$ is defined as the Spin Coherence Time (SCT). This quantity is important for EDM measurements in a storage ring since a polarization buildup would be noticeable only if the particles in the bunch remain spin-coherent.

2. – Design

The proposed design [4,5], shown in fig. 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 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 has a common power supply for centralized control. During this study, however, the SXSS and QSS magnets were turned off [6]. An RF-cavity is also placed at one of the straight

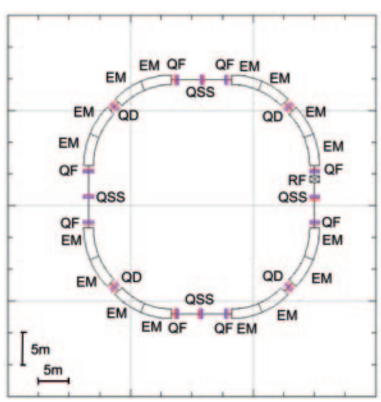

Fig. 1. – The floor plan of the prototype EDM ring. Dipoles are labelled with *EM*, quadrupoles corresponding to their family with *QF*, *QD* or *QSS* and the cavity with *RF*.

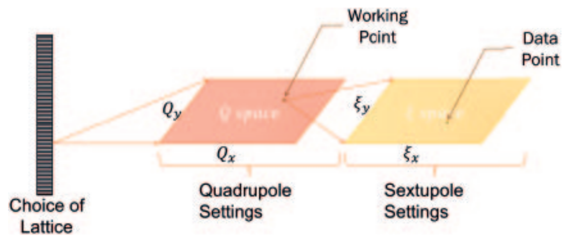

Fig. 2. – Organization of free parameters in the prototype EDM lattice. Each set of Q_x and Q_y (adjusted by the quadrupole field strengths) is a working point on the Q-space, and each set of ξ_x and ξ_y (adjusted by the sextupole field strengths) is a data point on the ξ-space.

sections for bunching (or longitudinal focussing) of particles. In the lattice used in this study, $\vec{E}$, $\vec{B}$ and γ values are optimized for frozen-spin particles of momentum of 294.057 MeV/c, a track-length of 123.36 m and a bending radius of 12.248 m.

3. – Parameter space

Given the lattice design described in the previous section, a Gaussian bunch of 1000 particles is simulated in BMAD [7], with beam emittances set to $\epsilon_{x,y} = 5 \times 10^{-7}$. The spin dynamics is 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], respectively. These parameters have been optimized according to the scheme shown in fig. 2.

This study aims to find the maximum value of the 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 sensitivity of the parameters on the SCT.

4. – Results

The SCT is measured by simulating a bunch of frozen-spin particles in 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 $|\vec{S}(t_c)| = \frac{1}{e}$. Simulations were run on a total of 1224 data points at 17 working points, starting with ($Q_x = 1.823$, $Q_y = 1.123$).

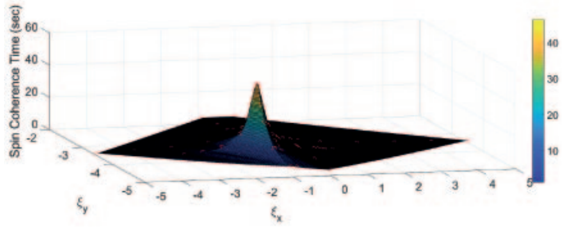

Fig. 3. – A surface plot of SCT values interpolated from 91 data points at $Q_x = 1.823$, $Q_y = 1.123$.

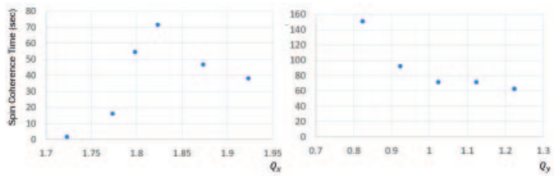

Fig. 4. – Results of the first two linear scans on the Q-space. In (a), $Q_y = 1.123$.The Q_x value in the first scan with the maximum SCT (1.823) was fixed during the subsequent perpendicular scan shown in (b).

4·1. *Maximum SCT*. – Initially, the first working point was explored. Points on the ξ-space were measured for their SCT and plotted as shown in fig. 3. Each working point has an associated ξ-space and a maximum SCT. The highest SCT measured so far is 150 s (marked in fig. 4(b)) 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.

5. – 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).

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