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SIMULATION AND OPTIMIZATION OF THE SPIN COHERENCE TIME OF PROTONS IN A PROTOTYPE EDM RING

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Abstract

The matter-antimatter asymmetry might be understood by investigating the EDM (Electric Dipole Moment) of elementary charged particles. A permanent EDM of a subatomic particle violates time reversal and parity symmetry simultanously and would be, with the currently achievable experimental accuracy, a strong indication for physics beyond the Standard Model. The JEDI-Collaboration (Jülich Electric Dipole moment Investigations) is preparing a direct EDM measurement for protons and deuterons in Jülich: first at the storage ring COSY (COoler SYnchrotron) and later at a dedicated storage ring. A prototype EDM ring is an intermediate step before building the final storage ring to demonstrate sufficient beam lifetime and SCT (Spin Coherence Time) in a pure electrostatic ring as well as in storage ring with combined electric and magnetic bending elements. In order to study the effect of E-B-deflectors on the orbit and the spin motion the software library Bmad is used. First results of spin simulations, with focus on the optimization of the SCT, towards the prototype EDM ring will be presented in the following.

INTRODUCTION

In order to explain the matter-antimatter asymmetry in the Universe, additional $\mathscr{C}\mathscr{P}$-violating processes are needed [1]. A non-vanishing EDM of a subatomic particle is a candidate for such a process. It is predicted by the Standard Model (SM), its magnitude, however, is expected to be unobservably small with current techniques. Measuring an EDM at a higher magnitude would be an indication for physics beyond the SM. The JEDI-Collaboration is aiming to measure an EDM using a storage ring. The interaction of a particles' spin with electromagnetic fields in a storage ring allows the direct measurement of an EDM. The underlying experiments for charged particles need to be performed with high-precision and require an accurate measure and control of the spin and the beam motion. For EDM measurement a dedicated ring has to be build. Before building a dedicated ring, the feasibility of an EDM measurement in a storage ring has to be shown and technical issues have to be clarified. Therefore, a prototype of this dedicated ring is planned [2]. For this prototype, spin tracking simulations using the Bmad Software Library have been performed to estimate the maximum achievable SCT [3].

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DESIGN

The current design of the prototype EDM ring consists of four unit cells that form four bending arcs [4,5]. Summing up all magnets placed in the basic form of the lattice, one ends up with eight dipoles and 16 quadrupoles (see Fig. 1). The quadrupoles can be grouped into three families with common power supplies. In the bending section, i.e., in between the bending dipoles of one unit cell, the quadrupoles of the first family were placed. This family was named 'QD' and contains a total of four quadrupoles in total. The quadrupoles around the bending dipoles of one unit cell form the next family, called 'QF', which contains a total of eight quadrupoles. The last family consist of those quadrupoles, which were placed in between the unit cells. These are named 'QSS' as they are placed in the straight sections of the storage ring. This family contains four quadrupoles and provides further flexibility to adjust the beam optics. In a very simple approach a sextupole was placed on top of every quadrupole. Also these sextupoles form three families which correspond to the quadrupole families. They are named corresponding to the quadrupole families they belong to with 'SXF', 'SXD' and 'SXSS'. In addition an RF-Cavity is placed inside one straight section. The special feature of the prototype EDM ring are electromagnetic dipole magnets, which provide combined electric and magnetic fields as well as pure electric fields for bending.

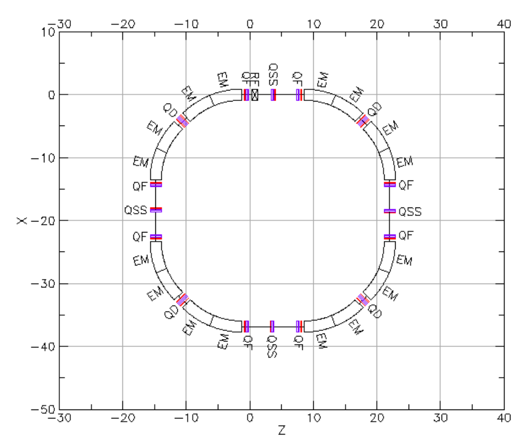

Figure 1: Output of the floor plan of prototype EDM ring from Tao [6]. Dipoles are labeled with 'EM', quadrupoles corresponding to their family with 'QF', 'QD' or 'QSS' and the cavity with 'RF'.

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The spin motion in presence of electromagnetic fields is described by the Thomas-BMT equation [7,8]. Knowing this and taking advantage of the combined fields in the dipoles, the reference particles' spin and momentum stay aligned during the precession in the prototype ring. This is called frozen spin and can only be achieved if the dipole fields are matched to the reference particle momentum (see Table 1).

Table 1: Particle Properties and Field Strengths for Frozen Spin of the Reference Particle in the Prototype EDM Ring

Property	Magnitude	Unit
Kinetic energy	45	MeV
β	0.299	
γ	1.048	
Dipole Length	9.620	m
Electric field E	5.061	MV/m
Magnetic field B	0.024	T

For spin tracking simulations regarding the prototype EDM ring, this design was implemented in Bmad, which is a subroutine library for charged particle tracking in storage rings [9]. By adjusting the two quadrupole families 'QF' and 'QD' a working point can be selected. A variation in the range from zero to two of the horizontal and vertical betatron tunes is possible using these families. The working point $Q_x = 1.823$, $Q_y = 1.123$ was chosen for spin tracking simulations as it provides low natural chromaticities of $\xi_x = -0.070$ and $\xi_y = +0.035$ and a large dynamic aperture [10]. The optics of this working point is shown in Fig. 2.

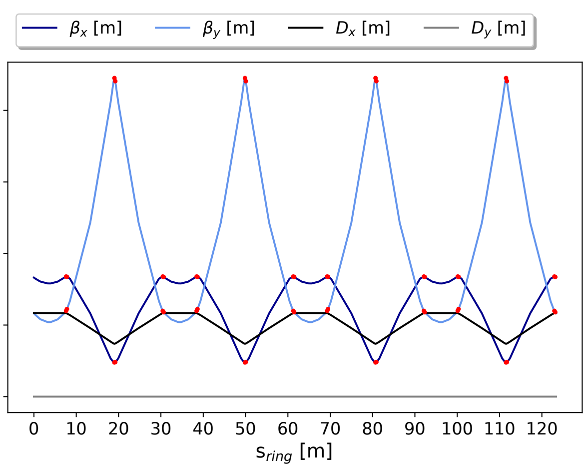

Figure 2: Optics of the chosen working point. The x-axis shows the position inside the storage ring and the y-axis the magnitude of the individual properties. Location of quadrupoles are marked with red dots.

To investigate the SCT, a particle beam has to be tracked. For this purpose, a proton beam consisting of 1000 particles was tracked for 10^6 revolutions (which corresponds to roughly 1 s). The beam center was placed on the closed orbit so offset particles are moving symmetrically around the reference orbit. Also pure longitudinal polarization at the beginning of the tracking algorithm was assumed for all particles in the bunch (see Table 2). Due to their offset from the reference particle in phase space the individual particles spin will start to rotate in the horizontal plane. This will lead to a depolarization of the particle bunch. The time until the total polarization falls below $1/e$ is called SCT.

Table 2: Beam Properties of the Beam Used for Spin Tracking Simulations To Investigate the SCT

Property	Selected	Property	Selected
Species	Proton	Distribution	Gaussian
$N_{Particles}$	1000	ϵ_x	0.5 µm
$N_{Bunches}$	1	ϵ_y	0.5 µm
Pol.	longitudinal	$\Delta p/p$	$1 \cdot 10^{-4}$

SIMULATION OF THE SPIN MOTION

The depolarization of a particle bunch can be reduced by adjusting system parameters like the chromaticities ξ_x and ξ_y. These were changed during the spin tracking simulations using the two sextupole families 'SXF' and 'SXD'. By observing the loss of total polarization of the beam, the time was estimated. To find the maximum SCT for the given working point one chromaticity was kept constant while the other one was varied. After finding the local maximum for the varied chromaticity, it was kept at the this value and the other chromaticity was varied until its local maximum was found. This procedure is sketched in Figs. 3 and 4 and was carried out until no further improvement of the SCT could be achieved. The result of this method is a 3D grid of chromaticity versus SCT (see Fig. 5).

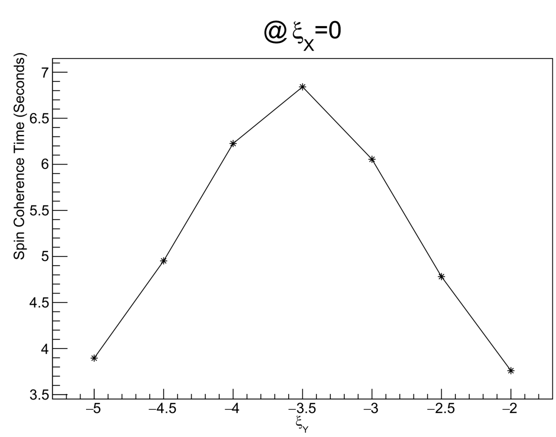

Figure 3: Variation of vertical chromaticity while keeping the horizontal chromaticity constant. The y-axis shows the SCT derived from the total polarization loss.

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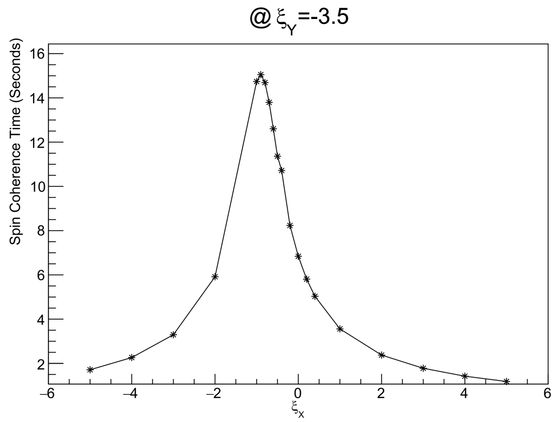

Figure 4: Variation of horizontal chromaticity while keeping the vertical chromaticity constant. The y-axis shows the SCT derived from the total polarization loss.

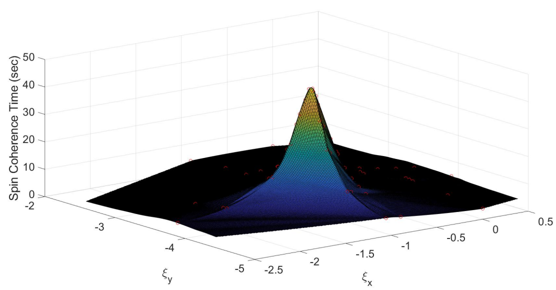

Figure 5: Variation of horizontal and vertical chromaticity. The z-axis shows the SCT derived from the total polarization loss.

The 3D grid shows that there is only one combination of horizontal and vertical chromaticities, where a maximum SCT is achieved. For the used working point, this combination is $\xi_x = -1.05$ and $\xi_y = -3.95$. The reason why the maximum SCT is not at $\xi_x = 0$, $\xi_y = 0$ is only partially understood and may be related to intrinsic spin resonances and additional decoherence caused by electric fields. For this reason, further investigation is needed.

CONCLUSION AND OUTLOOK

The current design of the proton prototype EDM ring was implemented into Bmad. A working point was determined at which the SCT in dependency of the horizontal and vertical chromaticity was investigated. It could be shown that at the given working point the SCT can be increased masssivly by varying the chromaticity of the ring. One point of optimal chromaticity was found, which is not in accordance with zero [11]. The reason why this combination of chromaticities allows maximal SCT is not fully understood. Further investigation is needed. Simulations for different working points are in progress to examine whether there is a fixed combination for the ring or if this combination depends on the working point. This enables the study of the influence of spin resonances on the SCT.

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