SIMULATIONS OF BEAM DYNAMICS AND BEAM LIFETIME FOR THE PROTOTYPE EDM* RING

S.Siddique[†][1],GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
A.Lehrach[2], J.Pretz[2], Forschungszentrum Jülich GmbH, Jülich, Germany
[1,2] also at III Physikalisches Institut B, RWTH Aachen University, 52056 Aachen, Germany
C.Carli, CERN,Geneva,Switzerland
on behalf of JEDI[‡] and CPEDM[§] Collaboration

Abstract

The matter-antimatter asymmetry may be explained through CP-violation by observing a permanent electric dipole moment (EDM) of subatomic particles. An advanced approach to measure the EDM of charged particles is to apply a unique method of "Frozen spin" on a polarized beam in a storage ring. To increase the experimental precision step by step and to study systematic effects, the EDM experiment will be performed within three stages: the magnetic ring COSY [1], a prototype EDM ring, and finally all electric EDM ring. The intermediate ring will be a mock-up of the final ring, which will be used to study a variety of systematic effects and to implement the basic principle of the final ring. The simulations of beam dynamics of the prototype EDM ring with different lattices are carried out to optimize the beam lifetime and minimize the systematic effects. The preliminary design of the prototype EDM ring helped to estimate the beam losses by using analytical formulas. Beam-target effects with more detailed simulations are being studied for beam losses. Further investigations to reduce systematic effects are also in progress.

INTRODUCTION

Explaining baryogenesis is one of the major challenges for modern physics. The matter-antimatter asymmetry riddle may be solved by observing the existence of permanent Electric Dipole Moments (EDM) of subatomic particles. The Standard Model of particle physics predicts non-vanishing EDMs, but their magnitude is too small to be detected with current techniques. However, the existence of permanent EDMs is only possible through charge and parity (*CP*) symmetry violation [1]. In the past, most of the EDM measurements were performed for neutral particle systems. But now dedicated measurements of the EDM for charged hadrons are also possible at storage rings where polarized beams are available.

JEDI is working on the investigation of EDMs of protons and deuterons. The proposed storage ring is to measure the EDM of the proton with all-electric elements for ultimate precision. However, this ring follows two stages (Precursor experiment at COSY and Prototype proton storage ring) to reduce systematic effects and increase the EDM measurement precision [2].

PRINCIPLE TO MEASURE EDM IN A STORAGE RING

The experimental method to measure an electric dipole moment of a fundamental particle or subatomic system relies on the spin precession rate in an external field. The spin motion can be understood by studying the Thomas-BMT equation:

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \left(\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}}\right) \times \vec{S} \tag{1}$$

where

$$\vec{\Omega}_{\mathrm{MDM}} = -\frac{q}{m}\left[G\vec{B} - \frac{\gamma G}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{B}) - \left(G - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] \tag{2}$$

$$\vec{\Omega}_{\mathrm{EDM}} = -\frac{\eta q}{2mc}\left[\vec{E} - \frac{\gamma}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{E}) + c\vec{\beta}\times\vec{B}\right]. \tag{3}$$

Where, $\vec{S}$ denotes the spin vector in the lab frame, t is the time in the laboratory system, $\vec{\beta} = \vec{v}/c$ and γ are the relativistic Lorentz factors, and $\vec{B}$ and $\vec{E}$ are the magnetic and electric fields respectively. G(magnetic anomaly) is a dimensionless quantity and η describes the strength of the EDM. The angular frequencies, $\vec{\Omega}_{\mathrm{MDM}}$ and $\vec{\Omega}_{\mathrm{EDM}}$, act through the magnetic dipole moment (MDM) and electric dipole moment (EDM) respectively. For a particle ensemble with a spin polarisation initially aligned along the momentum vector, if the "Frozen-spin" condition applies then the vertical polarisation build-up with time in response to the external radial electric field is due to the particle's EDM [2]. The change in polarisation direction can be determined by scattering the beam through a carbon target and analyzing the azimuthal distribution of the scattered particles. A vertical polarisation results in a left-right asymmetry in the detector. Fig. 1 describes the method to measure the EDM in the storage ring. The project to measure EDM of charged particles is divided into three stages. The precursor experiment at COSY Forschungszentrum Jülich is the starting point of this project. The effort to measure the EDM of deutrons in a magnetic storage ring is ongoing. The second stage is to build a small prototype storage ring of around 120 m in length. The third and last stage will be a fully electrostatic

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[*] Electric Dipole Moment

[†] s.siddique@gsi.de

[‡] Jülich Electric Dipole Moment Investigation

[§] Charged Particles Electric Dipole Moment

[1] Cooler Synchrotron Forschungszentrum Jülich, Germany

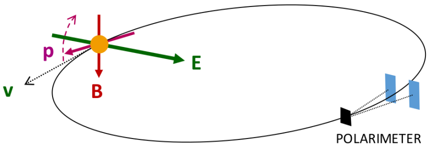

Figure 1: The diagram shows a particle motion around the storage ring under the influence of electromagnetic fields. The polarization, initially along the particle's momentum, precesses towards the vertical direction in response to the radial electric field acting on the EDM. The vertical component of the polarization is observed by scattering in the polarimeter [2].

ring with a circumference of about 500 m. The concept of these stages is to reduce systematic effects and increase the EDM measurement sensitivity. This paper focuses on 2nd stage of the project.

THE PROTOTYPE STORAGE RING (PTR)

The PTR layout is shown in Fig. 2. It will be operated in two different modes. The first mode will be an all-electric ring with $T = 30$ MeV protons, with the aim to store beam for a longer time (*i.e.* 1000 sec), to inject multiple polarization states and to develop and benchmark simulation tools. Whereas the second mode will be an electromagnetic ring with $T = 45$ MeV protons which will be used to measure EDM with the Frozen-spin method by counter-rotating beams simultaneously. In this paper, the first mode of PTR was considered to store a high beam intensity for a longer time, which requires a suitable lattice structure of the ring. Therefore, four different lattices with different vertical focusing strengths were studied in the context of beam losses.

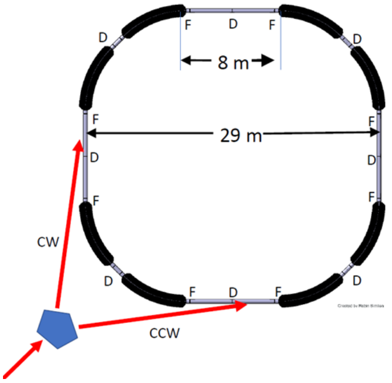

Figure 2: The basic layout of the PTR, consisting of eight electrostatic deflectors, three families of quadrupoles (horizontally focusing:QF, horizontally defocusing: QD and straight section: QSS), and two families of sextupoles with a total circumference of around 120 m [2].

BEAM SIMULATIONS

For the PTR, lattice optics is studied through the usage of *Methodical Accelerator Design* MAD-X [5] (the electrostatic bendings were defined by entering the transfer matrices). After generating the lattice optics for the PTR (electric mode), the beam losses are calculated using analytical formulas. Four lattices were studied in the following section with different optical functions.

Optical Functions

The spin dynamics in PTR design depend heavily on the vertical focusing structure of the storage ring. PTR can be tuned from ultra-weak to strong focusing, but stronger focusing leads to systematic effects, and weaker focusing causes beam loss. Thus, selecting a suitable lattice is crucial to balance beam lifetime and systematic effects. Different lattice types have been investigated for various vertical focusing strengths, resulting in four maximum vertical beta functions β_{y-max}. (see Fig. 3):

- Strong focusing lattice with $\beta_{y-max} = 33\,\mathrm{m}$
- Medium focusing lattice with $\beta_{y-max} = 100\,\mathrm{m}$
- Weak focusing lattice with $\beta_{y-max} = 200\,\mathrm{m}$
- Weaker focusing lattice with $\beta_{y-max} = 300\,\mathrm{m}$

After generating these lattices, beam loss estimations were performed for all major effects and in two different scenarios, with residual gas only and with a carbon target.

Beam Losses Estimation

Four major effects were considered for the immediate beam losses. These effects are Hadronic Interactions, Single Coulomb Scattering, Energy Loss Straggling, and Touschek Effect (*i.e.* IntraBeam Scatterings). The basic beam loss rate formula for hadronic and single coulomb scatterings is [3]:

$$1/\tau = n\sigma_{tot} f_{rev}, \tag{4}$$

where n is the residual gas or target density, σ_{tot} is the total cross-section and revolution frequency f_{rev} of the proton beam is 0.726 MHz for this ring. Nitrogen equivalent pressure $P_{N_2,eq} = 2.8 \times 10^{-11}$ Torr and 30µm thick target was considered for these calculations. In the presence of the internal target, the effects of the residual gas on the beam are negligible, since the thickness of the target is much greater than the integral density of the residual gas over the circumference of the ring. A beam of 10^9 particles and a transverse emittance of $\epsilon_{x,y} = 10$ mm mrad is taken into account for these processes.

The effect of hadronic interaction remains constant for all lattice structures, while the impact of Single Coulomb Scattering is determined by the total cross-sectional area σ_{tot}, which in turn is dependent on the dynamic aperture of the ring and betatron functions. As a result, minimizing betatron values can help reduce beam losses. Due to low beam energy and high longitudinal acceptance, the beam loss rate

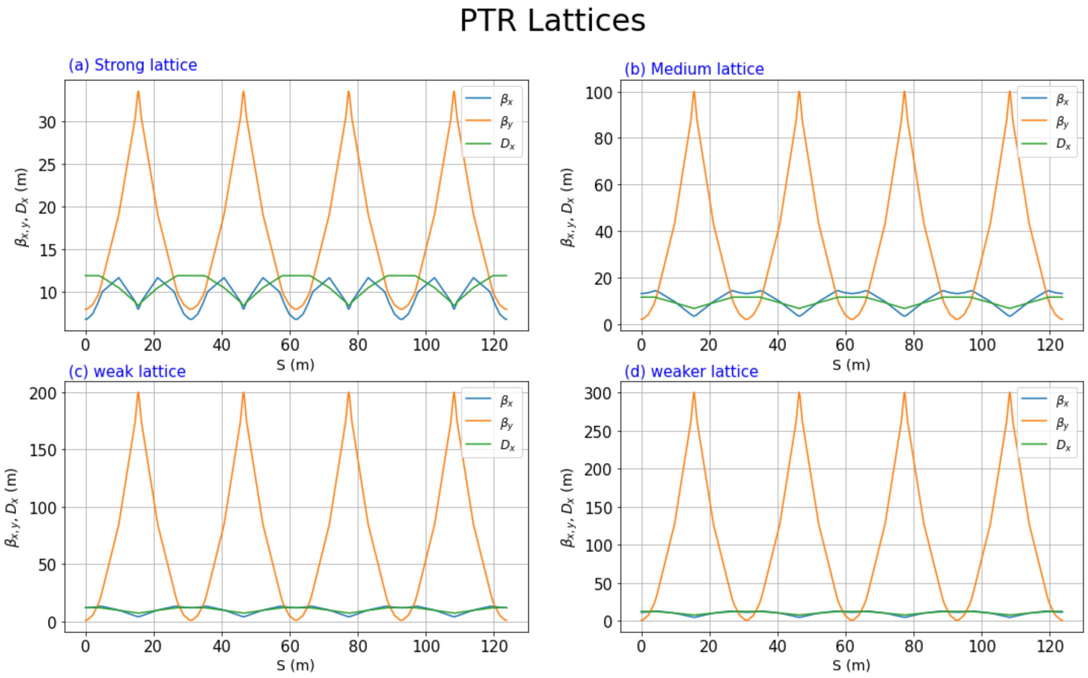

Figure 3: (a) is a strong focusing lattice with β_{y-max} = 33 m, (b) is a medium focusing lattice with β_{y-max} = 100 m, (c) is weak focusing lattice with β_{y-max} = 200 m, (d) is weaker focusing lattice with β_{y-max} = 300 m, β_x is a horizontal beta function and D_x is horizontal dispersion.

Lattice β_{y-max}	**H.I** $10^{-6}s^{-1}$	**SCS** $10^{-4}s^{-1}$	**IBS** $10^{-4}s^{-1}$	τ^{-1} $10^{-4}s^{-1}$
33 m	2.7	7.6	2.34	9.47
100 m		27.3	2.10	27.5
200 m		94.6	1.99	90.0
300 m		208	1.90	195

Table 1: The analytical formulas specified in [3] have been utilized to estimate the significant processes of H.I (Hadronic Interactions), SCS (Single Coulomb Scatterings), and IBS (IntraBeam Scatterings) for all four lattices. Based on these estimations, the total beam loss rate τ^{-1} has been computed.

from energy loss straggling is minimal, allowing particles to remain stable in the longitudinal bucket after losing a small amount of energy. On the other hand, the Touschek effect varies for different lattices, both in terms of the beam and the lattice, leading to varying results. Consequently, only three processes are essential in determining the total beam loss rate, as shown in the table 1. These calculations show that as β_{y-max} is getting higher, the beam loss rate is also increasing which causes a shorter beam lifetime. Hence, to store the beam for 1000 sec in the PTR, a lattice with β_{y-max} below 100 m would be preferable.

After getting results from rough analytical formulas, another software BetaCool [4] was used to perform beam loss calculations. BetaCool is used because it enables a more realistic description of the storage ring. A very good agreement between analytical calculations and Betacool results was observed, which can be seen in figure 4.

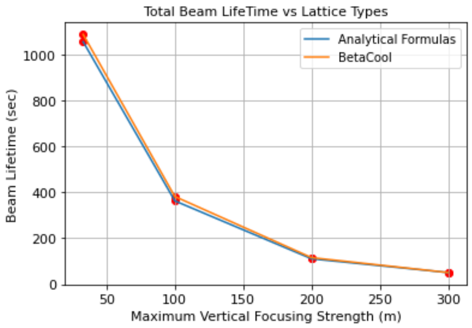

Figure 4: This plot shows a comparison of analytical formulas and BetaCool results in the form of beam lifetime vs lattice types (in terms of their maximum vertical betatron function β_{y-max}).

SUMMARY AND CONCLUSION

In summary, the lattice with vertical focusing strength (*i.e.* $\beta_{y-max} \leq 100$ m) can be considered a reasonable choice for a longer beam lifetime and BetaCool also supported these results. However, a deeper study of beam-target interaction may help us to gain further longer beam lifetime as the target is a dominant candidate for beam losses. Therefore, beam tracking for beam-target interaction is in progress.

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