PROCEEDINGS OF SCIENCE

Simulations Of Beam Losses For The Prototype Electric Dipole Moment Storage Ring

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on behalf of JEDI*[†] *and CPEDM*[‡] *Collaborations

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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 an accelerator. To increase the experimental precision step by step and to study systematic effects, the EDM experiment can be performed within three stages: the magnetic ring COSY (Cooler Synchrotron storage ring at Forchungszentrum Jülich), a prototype EDM ring, and finally the 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 prototype EDM ring with different lattices are performed to optimize the beam lifetime and to minimize the systematic effects. The preliminary design of the prototype EDM ring helped to estimate the beam losses by using analytical formulas. Further investigations on enhancing EDM measurement precision and reducing systematic effects are in process.

This Proceeding is the same as submitted to IPAC23, 7-12 May, Venice Italy

19th Workshop on Polarized Sources, Targets and Polarimetry (PSTP2022),
26-30 September 2022
Mainz, Germany

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PoS(PSTP2022)023

1. 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.

The JEDI Collaboration is working on the investigation of EDMs of protons and deutrons. 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].

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

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

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

Here, $\vec{S}$ 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 illustrates 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

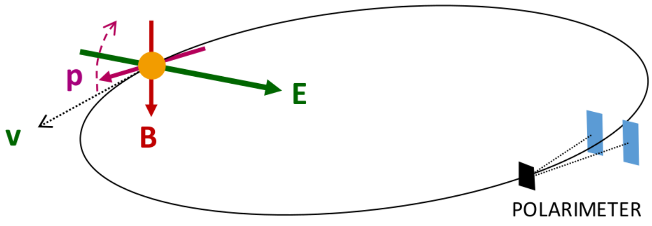

Figure 1: The diagram shows a particle motion around the storage ring under the influence of electromagnetic fields. The polarization, initially along the particle's momentum, precesses towards the vertical direction in response to the radial electric field acting on the EDM. The vertical component of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

a small prototype storage ring of around 120 m in circumference. The third and last stage will be a fully electrostatic 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.

3. 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 the 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.

4. Beam Simulations

For the PTR, lattice optics is studied through the usage of *Methodical Accelerator Design* MAD-X [4] (the electro-static 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.

4.1 Optical Functions

In the PTR design, the spin dynamics strongly depend on the vertical focusing structure of a strong ring. Therefore, different lattice types have been investigated for different vertical focusing strengths, resulting in four different maximum vertical beta functions β_{y-max} (see Fig. 3):

- Strong focusing lattice with $\beta_{y-max} = 33$ m

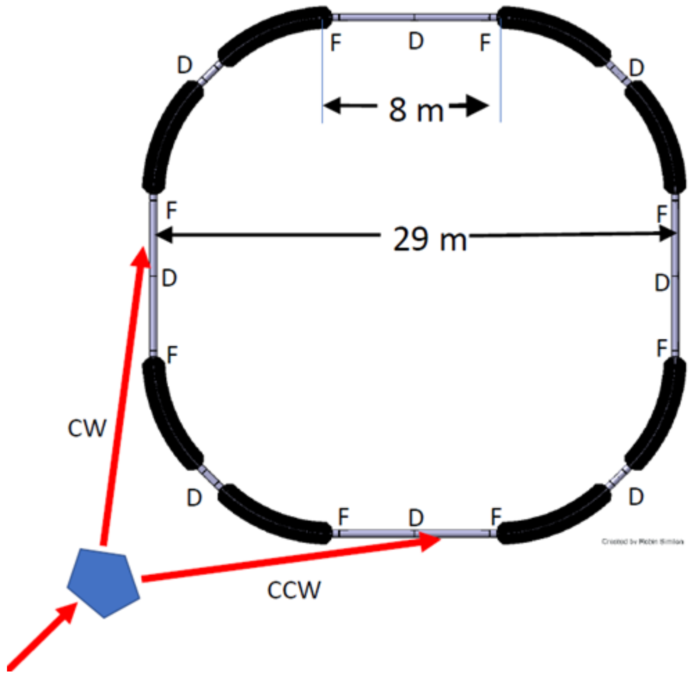

Figure 2: The basic layout of the PTR, consisting of eight electrostatic deflectors, three families of quadrupoles (horizontally focusing:QF, horizontally defocusing: QD and straight section: QSS), and two families of sextupoles with a total circumference of around 120 m [3].

- Medium focusing lattice with β_{y-max} = 100 m
- Weak focusing lattice with β_{y-max} = 200 m
- Weaker focusing lattice with β_{y-max} = 300 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.

4.2 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 [5]:

$$1/\tau = n\sigma_{tot} f_{rev}, \tag{2}$$

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 $P_{N_2,eq}$ = 2.8×10^{-11} Torr and 30 µm 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.

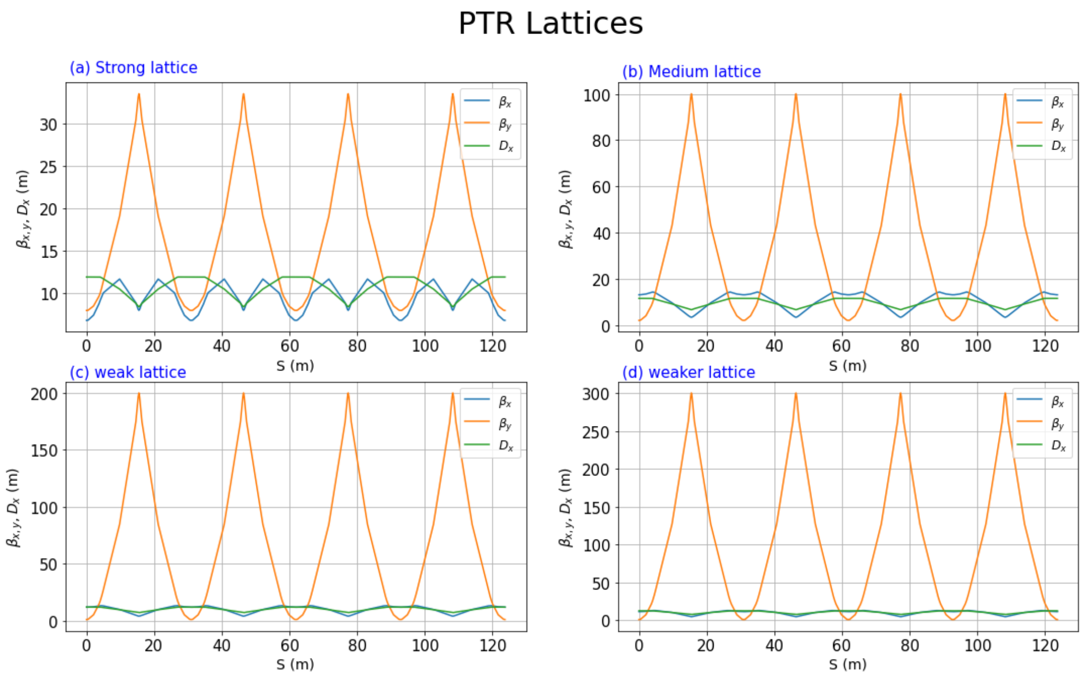

Figure 3: (a) is a strong focusing lattice with β_{y-max} = 33 m, (b) is a medium focusing lattice with β_{y-max} = 100 m, (c) is weak focusing lattice with β_{y-max} = 200 m, (d) is weaker focusing lattice with β_{y-max} = 300 m, β_x is a horizontal beta function and D_x is horizontal dispersion.

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: Estimations of all major processes H.I (Hadronic Interactions), SCS (Single Coulomb Scatterings), and IBS (IntarBeam Scatterings) for all four lattices leading to the total beam loss rate τ^{-1}.

The hadronic interaction effect is independent of the lattice structure, so it produces the same result for all lattices. The beam loss rate due to energy loss straggling is close to zero because of low beam energy and high longitudinal acceptance. After a small energy loss, the particles remain in the stable part of the longitudinal bucket and are not lost. Therefore, only three processes are crucial for the total beam loss rate which can be seen in 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 [6] 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.

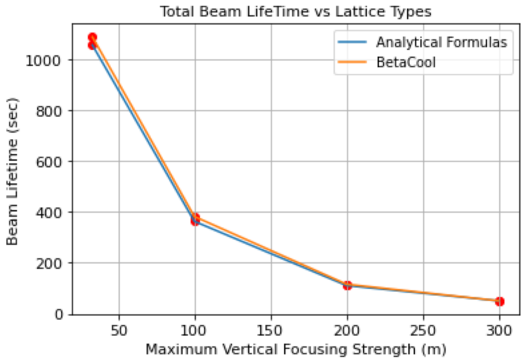

Figure 4: This plot shows a comparison of analytical formulas and BetaCool results in the form of beam lifetime vs lattice types (in terms of their maximum vertical betatron function β_{y-max}).

5. 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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