Simulations of Beam Dynamics and Beam Lifetime for a Prototype Electric Dipole Moment Ring

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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), 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 prototype EDM ring with different lattices are performed to optimize the beam lifetime and to minimize the systematic effects. The preliminary design of prototype EDM ring helps to estimate beam losses by using analytical formulas.

KEYWORDS: Electric Dipole moment, CP-violation, Beam Dynamics, Beam Lifetime

1. Introduction

Explaning the baryogenesis is one of the major challenges for modern physics. The matter-antimatter asymmetry riddle may be solved by observing a permanent existence of the 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 Jülich Electric Dipole moment Investigations (JEDI) collaboration at Forschungszentrum Jülich, Germmany is working on the investigation of EDMs of protons and deutrons. The future plan of JEDI is to measure the EDM of charged particles in a storage ring under the influence of electromagnetic fields with the help of new technique called "Frozen Spin". This technique demands to align the polarization parallel to particle's momentum, thus vertical polarization build up gives a access to measure EDM. The purposed 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. One of the possible ways to reduce systematic effects is the use of counter-rotating beams simultaneously in an all electric ring [2].

2. Principle to Measure EDM in a Storage Ring

The experimental method to measure an electric dipole moment of fundamental particle or sub-atomic system relies on the spin precession rate in an external field. The spin motion can be understood by studying the Thomas-BMT, given in equation (1) and for more details see [3, 4].

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

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, $\beta = v/c$ and γ are the relativistic Lorentz factors, and B and 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, the vertical polarisation build up with time in response to external radial electric field is due to particle's EDM. The change in polarisation direction can be determined by scattering the beam off a carbon target and analyzing the azimuthal distribution of the scattered particles. A vertical polarisation results in an left-right asymmetry in the detector. Fig. 1 describes the method to measure the EDM in the storage ring.

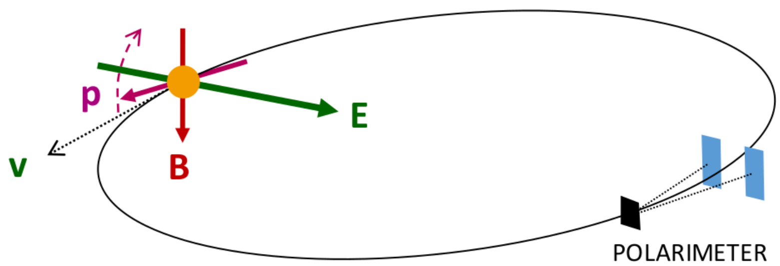

Fig. 1. Diagram shows a particle motion around the storage ring under the influenence of electromagnetic fields. The polarization, initially along the particle's momentum, precesses towards the vertical direction in response to the radial electric field acting on the EDM. The vertical component of the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

The project to measure EDM of charged particles is divided into three satges. The precursor experiment at COSY Forshungszentrum Jülich is a starting stage of this project. The effort to measure EDM of deutrons in a magnetic storage ring is ongoing. A special device called radio frequency (RF) Wein Filter is being used for this purpose [5]. 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 ring with circumference of about 500 m. The concept of these stages is to reduce systematic effects and increase EDM measurement sensitivity. The following discussion is only about the prototype storage ring.

3. The Prototype Storage Ring (PTR)

The PTR layout is shown in Fig. 2. It will be operated in two different modes. These two modes will serve different goals which are discussed below. The first mode will be an all-electric ring with $T = 30$ MeV protons and the second mode will be an electro-magnetic ring with $T = 45$ MeV protons. The first mode will help to gain the following goals:

- Storage of high intensity beams for sufficiently longer time (*i.e.* 1000 s).
- Injection of multiple polarization states (longitudinal and transverse) in clockwise (CW) and counter-clockwise (CCW) direction.
- Prevention of beam blow-up by electron cooling before injection or introducing stochastic cooling in the ring.
- Development and benchmarking of simulation tools.

The second mode will lead us to achieve further goals:

- Capability of the frozen spin method with simultaneously counter rotating beams.
- Introduction of magnetic shielding to minimize radial magnetic field components.
- Measurements of both CW and CCW polarized beams with a single target.

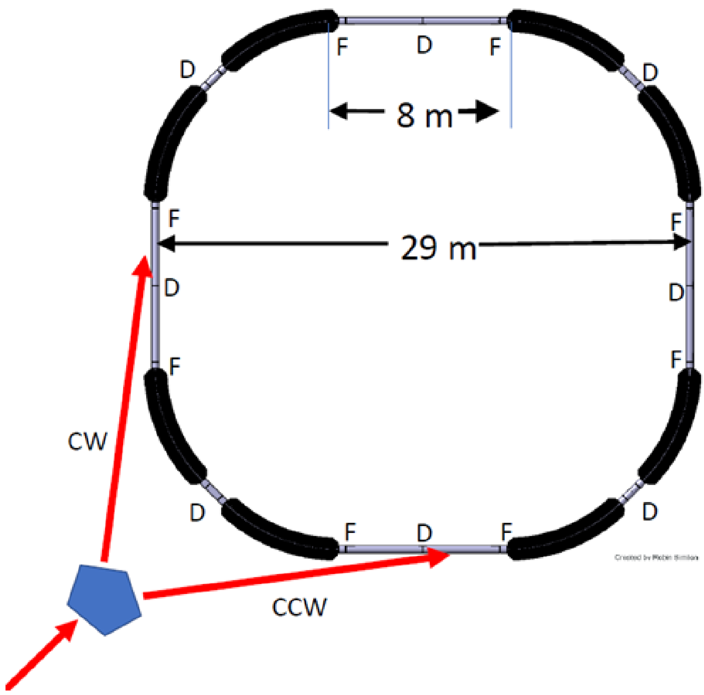

Fig. 2. Right side: The basic layout of the PTR, consisting of eight electrostatic deflectors, three families of quadrupoles (horizontally focusing:QF, horizontally defocusing :QD and straight section: QSS) and two families of sextupoles with total circumference of around 120 m

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Parameter	Electric mode	Electromagnetic mode	unit
Kinetic Energy (T)	30	45	MeV
$\beta = v/c$	0.247	0.299	
Momentum (pc)	239	294	MeV
Magnetic rigidity $B\rho$	0.798	0.981	T m
Electric rigidity	59.071	87.941	MV
γ (Lorentz factor)	1.032	1.048	
Emittance ($\epsilon_x = \epsilon_y$)	10	10	mm mrad

Table I. Basic beam parameters of PTR for both modes [2]

The storage of high beam intensity for longer time requires a suitable lattice structure of the ring, which can reduce systematic effects and enhance EDM measurements of charged particles. Therefore, four different lattices with different vertical focusing strengths were studied in context of beam losses. Four main effects of beam losses were considered for each lattice, which helped to develop a better lattice structure with high beam lifetime and smaller systematic effects.

4. Beam Simulations

For the PTR, lattice optics is studied through the usage of *Methodical Accelerator Design* MAD-X [7]. After generating the lattice optics for the PTR (electric mode), the beam losses are calculated using the 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 depends on the the vertical focusing structure of a strong ring. Therefore, different lattice types have been investigated for different vertical focusing strength, resulting in four different maximum vertical beta function β_{y-max} (see Fig. 3):

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

II Medium focusing lattice with $\beta_{y-max} = 100$ m

III Weak focusing lattice with $\beta_{y-max} = 200$ m

IV Weaker focusing lattice with $\beta_{y-max} = 300$ m

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

4.2 Beam Losses Estimation

This section is dealing with an estimation of beam losses by considering some of the main processes in the storage ring. These processes contribute to beam emittance blow-up, reduction of beam intensity, and consequently lead to particle losses. These effects are (1)Hadronic Interactions, (2) Coulomb Scattering, (3) Energy Loss Straggling, (4) Intra Beam Scattering.

The basic beam loss rate formula for hadronic and coulomb scatterings is [8]:

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

where n is the particle density, which in this case is $5.30 \cdot 10^5$ atoms /cm^3. Here, we assume a composition of hydrogen and nitrogen in the ratio of 80:20 respectively and σ_{tot} is total cross section.

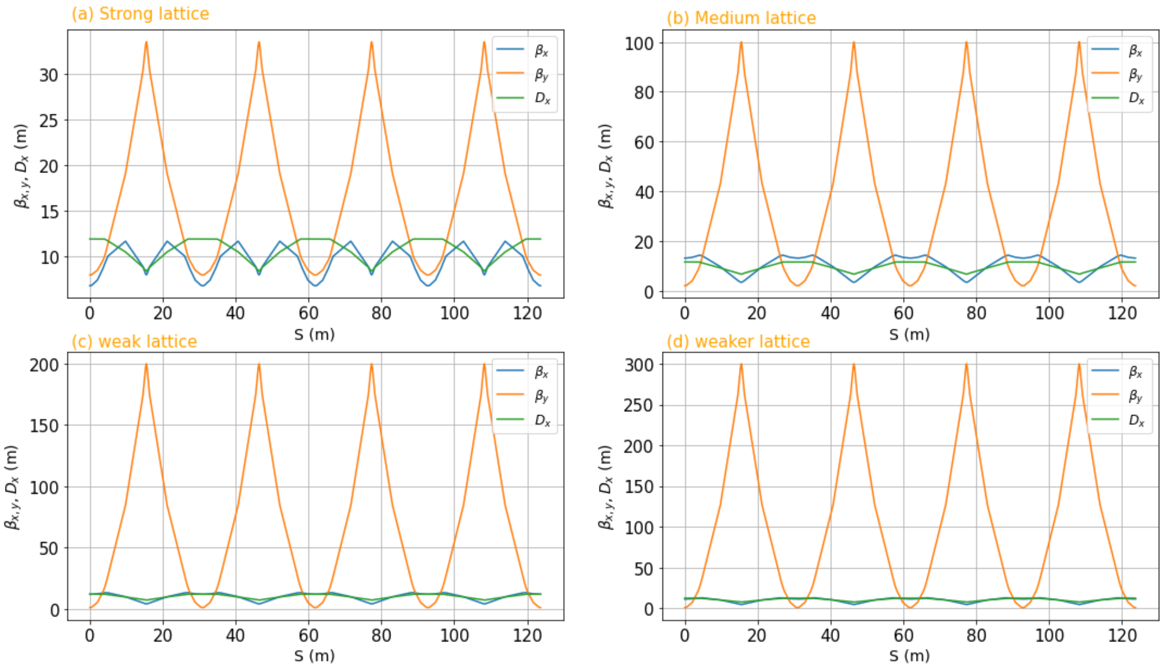

Fig. 3. Upper side : (a) is strong focusing lattice with $\beta_{y-max} = 33$ m , (b) is medium focusing lattice with $\beta_{y-max} = 100$ m, (c) is weak focusing lattice with $\beta_{y-max} = 200$ m , (d) is weaker focusing lattice with $\beta_{y-max} = 300$ m, β_x is horizontal beta function and D_x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

The revolution frequency f of the proton beam is 0.726 MHz for this ring. The used nitrogen partial pressure is $P_{N_2,eq} = 2.8 \times 10^{-11}$ Torr and the hydrogen effective target thickness is $4.0 \cdot 10^{13}$ atoms /cm^2. In the presence of an 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 hadronic interaction effect is independent on 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 and beam lifetime, which are listed below in table II.

Lattice	H.I (s^{-1})	C.S (s^{-1})	IBS (s^{-1})	$1/\tau_{tot}$(s^{-1})	τ_{tot}(s)
$\beta_{y-max} = 33$ m	$6.884 \cdot 10^{-6}$	$3.017 \cdot 10^{-4}$	$2.339 \cdot 10^{-4}$	$5.425 \cdot 10^{-4}$	1843
$\beta_{y-max} = 100$ m	$6.884 \cdot 10^{-6}$	$9.444 \cdot 10^{-4}$	$2.103 \cdot 10^{-4}$	$1.162 \cdot 10^{-4}$	806
$\beta_{y-max} = 200$ m	$6.884 \cdot 10^{-6}$	$2.685 \cdot 10^{-3}$	$1.991 \cdot 10^{-4}$	$2.891 \cdot 10^{-3}$	346
$\beta_{y-max} = 300$ m	$6.884 \cdot 10^{-6}$	$5.413 \cdot 10^{-3}$	$1.904 \cdot 10^{-4}$	$5.610 \cdot 10^{-3}$	178

Table II. Estimations of all major process H.I (hadronic Interactions), C.S (Coulomb Scatterings) and IBS (IntraBeam Scatterings) for all four lattices leading to the total beam loss rate $1/\tau_{tot}$ and the total beam lifetime τ_{tot}

These calculations show that the strong focusing lattice has a longer beam lifetime and the weaker the focusing gets, the more the beam loss rate increases. For EDM measurement, spin coherence time needs to be 1000 s and beam lifetime should also be longer than 1000 s. Therefore, a lattice should be chosen with vertical beta focusing below 100 m.

5. Summary and conclusion

In summary, the lattice with focusing strength below 100 m can be considered as a reasonable choice for longer beam lifetime. However, these calculations are preliminary which are further being investigated with carbon target and with simulation tools like BetaCool [9] to get more accurate results. The systematic errors of spin motion for the different lattice types are still being investigated using spin tracking simulations.

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