FEASIBILITY STUDIES OF THE STOCHASTIC COOLING SYSTEM IN THE PROTON STORAGE RING EDM EXPERIMENT*

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Abstract

This study explores the feasibility of implementing stochastic cooling in the proposed proton electric dipole moment (pEDM) storage ring to be constructed at Brookhaven National Laboratory. Investigating fundamental physics phenomena, such as the electric dipole moment (EDM) of protons, demands highly precise experimental setups. In such precision experiments, intra-beam scattering (IBS) causes emittance growth, which degrades beam quality and limits the spin coherence time (SCT), a key parameter for sensitive EDM detection. The integration of a stochastic cooling system for stored polarized proton beams offers a potential solution by mitigating the effects of IBS, suppressing emittance growth, stabilizing beam dynamics, and enhancing the overall efficiency of the storage ring. This paper examines the feasibility of incorporating such a system into the proton EDM storage ring and evaluates its potential to preserve beam polarization and quality, both essential for advancing EDM experiment.

INTRODUCTION

The proton Electric Dipole Moment (pEDM) experiment is the first direct search for proton EDM, aiming to probe Standard Model predictions of any particle EDM [1]. Using a storage ring with "frozen-spin" methodology to detect minute vertical polarization rotations [2], it builds on successful Muon g-2 techniques from Fermilab, Brookhaven, and CERN for long-term charged particle storage with precise spin tracking [3–5]. This paper discusses recent development on pEDM experiment, beam optics design, intra-beam scattering effects, and beam cooling requirements for preserving beam quality and spin coherence time.

The detection of a proton electric dipole moment through storage ring experiments has captivated particle physicists for several decades [6–9]. Recent advances have introduced a novel hybrid storage ring configuration designed to eliminate primary systematic uncertainties under the frozen spin approach. This innovative design employs electric bending plates to guide the polarized proton beam while implementing magnetic focusing in place of electric focusing. The magnetic focusing configuration enables simultaneous clockwise and counterclockwise beam storage, effectively canceling systematic errors associated with out-of-plane dipole electric fields. Systematic uncertainties from quadrupole electric fields can be mitigated through sequential runs employing magnetic focusing of varying intensities [9].

Experimental Technique

The spin $\vec{S}$ precession rate for a particle at rest in the presence of magnetic $\vec{B}$ and electric $\vec{E}$ fields is given by

$$\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}, \tag{1}$$

where magnetic and electric dipole moments are defined as $\vec{\mu} = (gq/2m)\,\vec{S}$ and $\vec{d} = (\eta q/2mc)\,\vec{S}$, respectively. Hence, the above Eq. (1) can be written as

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}, \tag{2}$$

where $\vec{\Omega} = \vec{\omega}_a + \vec{\omega}_\eta$, ω_a and ω_η stand for precession due to magnetic and electric dipole moments, respectively. For $\vec{\beta} \cdot \vec{E} = 0$ and $\vec{\beta} \cdot \vec{B} = 0$, the motion of the spin vector based on T-BMT [10] simplifies,

$$\vec{\omega}_a = -\frac{q}{m}\left[G\vec{B} - \left(G - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta} \times \vec{E}}{c} + \frac{\vec{B}_\parallel}{\gamma} - \frac{(\vec{\beta} \times \vec{E})_\parallel}{c\beta^2} \right], \tag{3}$$

$$\vec{\omega}_\eta = -\frac{\eta q}{2m}\left[\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right], \tag{4}$$

$$\vec{\Omega} = \vec{\omega}_a + \vec{\omega}_\eta, \tag{5}$$

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}. \tag{6}$$

Here $\parallel$ represents horizontal (in-plane) projection of a vector and G stands for the proton magnetic anomaly.

Setting $\vec{B} = 0$ and selecting the "magic momentum" $\gamma = \sqrt{1 + 1/G}$ yields the optimal conditions to run this experiment. For protons, the "magic" parameters are given in Table 2. With these parameters, Eq. (3) becomes

$$\vec{\omega}_a = \frac{q}{m\gamma c\beta^2}(\vec{\beta} \times \vec{E})_\parallel. \tag{7}$$

It is now clear that a vertical electric field would generates a nonzero radial component for $\vec{\omega}_a$, which would look like the EDM signal with one beam direction. With horizontal $\vec{E}$ field and $\vec{\beta}(\vec{E} = \vec{E}_\parallel, \vec{\beta} = \vec{\beta}_\parallel)$, the above condition simplifies further into $\vec{\omega}_a = 0$, which is also known as the *frozen spin* condition. In this arrangement, the spin precesses into the vertical direction only due to the EDM contribution,

$$\Omega \propto \eta E, \tag{8}$$

linearly in the timescale of the injection $\Omega \propto dS_y/dt$. And hence $dS_y/dt \propto \eta E$ is the fundamental principle of measuring the proton EDM. The magic momentum parameters for the proton is given in the following Table 1.

Table 1: "Magic" Momentum Parameters for Protons

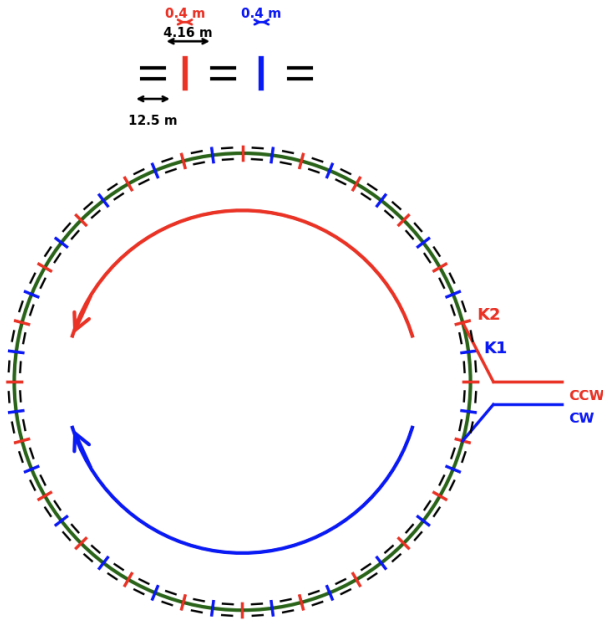| G	β	γ	p	KE
1.793	0.598	1.248	0.7 GeV/c	233 MeV

Figure 1: Schematic of symmetric-hybrid ring design: dark parallel bars– electrostatic deflecting plates with length – 12.5 m, K_1, K_2 – magnetic quadrupoles with each length – 0.4 m.

Lattice Design

The symmetric-Hybrid ring design used in this study consists of 24 FODO sections with total 800 m ring circumference. Each FODO section consists a pair of electric bending sections and a pair of magnetic quadrupoles. A schematic of the ring is given in Fig.1. The beamline optics and dispersion functions are shown in Fig. 2. A storage ring EDM experiment lattice design must achieve high tolerance to systematic errors, maintain reasonable alignment specifications for lattice elements, optimize peak magnetic and electric field strengths, accommodate both clockwise and counterclockwise beam injection, and meet realistic cost constraints. The ring and beam parameters for such a symmetric-hybrid ring design is presented in Table 2 [2].

BEAM EMITTANCE AND INTRA-BEAM SCATTERING

Intra-beam scattering is caused by multiple small-angle Coulomb scattering of charged particles within an accelerator beam. This scattering process couples the beam emittances in all three dimensions and eventually leads to emittance growth [11, 12]. In such precision experiments, intra-beam scattering (IBS) causes emittance growth, which degrades beam quality and limits the spin coherence time (SCT), a key parameter for sensitive EDM detection [13, 14].
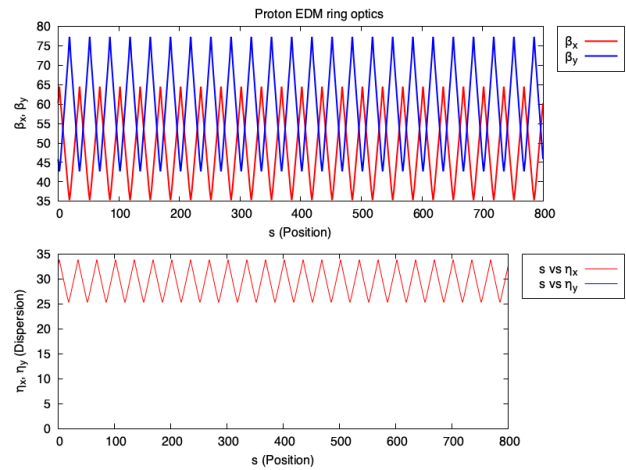

Figure 2: Twiss and dispersion functions in pEDM ring.

Table 2: Ring and Beam Parameters for the Symmetric-Hybrid Ring Design

Quantity	Value
Bending radius R_0	95.49 m
Number of periods	24
Electrode spacing	4 cm
Electrode height	20 cm
Deflector shape	Cylindrical
Radial bending E field	4.4 MV/m
Quadrupole length	0.4 m
Quadrupole strength	±0.21 T/m
Bending section length	12.5 m
Bending section circumference	600 m
Total circumference	800 m
Revolution time	4.46 μs
β_x^{max}, β_y^{max}	64.54 m, 77.39 m
Dispersion, D_x^{max}	33.81 m
Tunes, Q_x, Q_y	2.699, 2.245
Slip factor, $\eta_t / \frac{dp}{p}$	-0.253
Momentum acceptance, (dp/p)	5.2×10^{-4}
RMS emittance (mm·mrad), ϵ_x, ϵ_y	0.214, 0.250
RMS momentum spread	1.177×10^{-4}
Particles per bunch	1.17×10^8
RF voltage	1.89 kV
Harmonic number, h	80
Synchrotron tune, Q_s	3.81×10^{-3}
Bucket height, $\Delta p/p_{\mathrm{bucket}}$	3.77×10^{-4}
Bucket length	10 m
RMS bunch length, σ_s	0.994 m

To calculate the IBS rates for the given beam parameters from Table 2, we use the method explained in the reference [15]. This method uses small-angle multiple intra-beam scattering (IBS) emittance growth rates based integrals, which require a numeric evaluation at various locations of the accelerator lattice. The evolution of transverse and longitudinal beam dynamics with time due to IBS are shown in Fig. 3 and in Fig. 4 respectively.
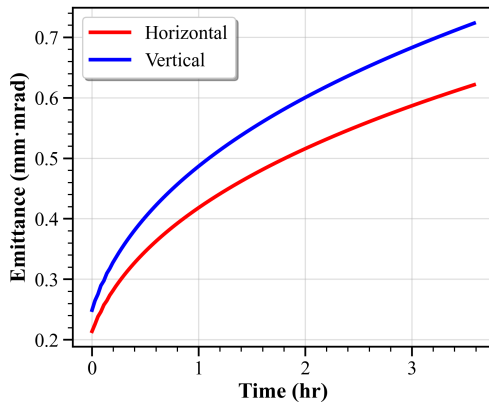
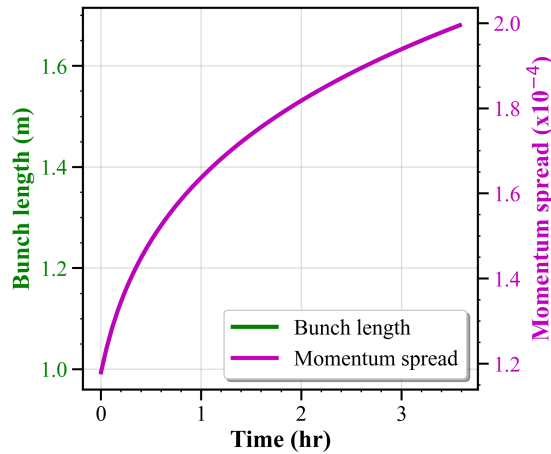Figure 3: Evolution of transverse beam emittances due to IBS.

Figure 4: Evolution of momentum spread and bunch length due to IBS.

Electron cooling effectively controls emittance growth from IBS and gas scattering [16], but its required longitudinal magnetic fields interfere with spin precession [17]. Therefore, it is unsuitable for the EDM experiment, and alternative cooling methods are needed for polarized proton beams.

STOCHASTIC COOLING

In the proton electric dipole moment (pEDM) experiment, preserving low beam emittance is critical for maintaining the frozen-spin condition. Natural effects like intra-beam scattering and gas interactions increase emittance over time, reducing spin coherence. Stochastic cooling, using broadband feedback via pickups and kickers, offers an effective solution. We adopt the bunched beam stochastic cooling methods demonstrated in prior storage rings and colliders [18, 19] for the pEDM ring. Table 3 presents basic cooling parameters to evaluate the cooling times.

Cooling Times

Stochastic cooling reduces beam emittance by correcting statistical density fluctuations (Schottky noise) using a feedback system. Pickup electrodes detect fluctuations propor-

Table 3: Stochastic Cooling Parameters

tQuantity	Value
Total no. of particles	2×10^8
RMS bunch length σ_s	1.0 m
No. of bunches n_b	80
Total circumference C	800 m
N_{eff}	5.3×10^{10}
Aperture limit, A_x	2 cm
f_{max}	3.5 GHz
Longitudinal cooling range n_σ	5
Overlap frequency f_{ovl}	1.9 GHz
Band-width, W	0.5 GHz
f_{max} with f_{ovl}	1.0 GHz
Initial longitudinal cooling time τ	2 min.
Initial IBS time, τ	30 min.

tional to $\sqrt{N}$, which are amplified and applied as corrective kicks via kicker electrodes. The effective number of particles cooled is given by $N_{\text{eff}} = N_{\text{tot}} \times (C/n_b\sqrt{2\pi}\sigma_s)$. The maximum useful frequency is limited by aperture effects, $f_{\text{max}} = \gamma\beta c/(\pi A_r)$, and by harmonic overlap, $f_{\text{ovl}} = f_0/(4|\eta|\sigma_p)$, to avoid destructive interference.

Cooling time is estimated using formula: $\tau = \left(8\sqrt{\pi}W/(3n_\sigma N_{\text{eff}})\right)^{-1}$, where W is the bandwidth, n_σ the cooling range, and N_{eff} the effective particle number. For typical parameters ($f_{\text{max}} = 1$ GHz, $W = 0.5$ GHz, $N_{\text{eff}} = 5.3 \times 10^{10}$), longitudinal cooling times of ~2 minutes are achievable—well below typical IBS times (30 minutes). Similar principles apply to transverse cooling, with adjustments for betatron motion and tune spread [20].

FUTURE WORK

A Python simulation code is being developed to model bunched beam stochastic cooling for polarized protons in the proposed EDM ring, and will be benchmarked against validated RHIC simulations to ensure reliable predictions for ring design and optimization.

SUMMARY

The proton EDM ring experiment aims for unprecedented sensitivity to CP violation beyond the Standard Model. A key challenge is sustaining long spin coherence times amid emittance growth from intrabeam scattering and gas interactions. Stochastic cooling addresses this by reducing emittance and stabilizing beam dynamics. Studies show that with well-designed pickup/kicker systems and GHz-range feedback, stochastic cooling is viable for polarized protons at EDM energies, improving beam quality and enabling sensitivity to EDM signals at the 10^{-29} e·cm level.

ACKNOWLEDGEMENT

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