



Quasi-frozen spin for both deuteron and proton beams in a periodic EDM storage ring lattice

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Abstract

A novel experimental setup with spatially separated magnetic and electrostatic fields is proposed for the study of proton and deuteron electric dipole moments (EDMs). The lattice design, which employs a spin compensator to achieve the “quasi-frozen” spin condition for precise measurements, demonstrates adaptability to existing facilities for high-energy physics research.

Keywords Electric dipole moment · Quasi-frozen spin · Wien filter · Electrostatic deflector

1 Introduction

The search for the electric dipole moment (EDM) of fundamental particles, such as protons and deuterons, constitutes a critical endeavor in contemporary physics. The EDM offers a unique opportunity to probe CP violation and validate theoretical models that describe particle interactions beyond the framework of the standard model [1, 2]. Precision EDM measurements of charged particles in accelerator facilities require the development of novel methods and techniques, as well as adaptations of existing facilities to meet stringent experimental conditions [3].

This paper proposes a versatile lattice concept featuring an interplay between spatially separated magnetic and electrostatic fields, specifically designed to facilitate EDM

studies of both deuterons and protons. Special attention is paid to the utilization of Wien filters or electrostatic deflectors with a kicker to compensate for the magnetic dipole moment (MDM) precession and to establish conditions conducive to a quasi-frozen spin (QFS) state. The presented analysis demonstrates the adaptability of this concept to a facility not originally designed for such experiments and explores its potential for promoting EDM research at higher-energy ranges, as well as for axion-like particle searches.

2 Quasi-frozen spin in a periodic lattice

The spin behavior of a particle ensemble can be represented by means of a classical vector, and its dynamics in external electromagnetic fields is described by the Thomas–Bargmann–Michel–Telegdi (T-BMT) equation [4]

$$\begin{aligned} d\vec{S}/dt &= (\vec{\Omega}_{\text{MDM}} + \vec{\Omega}_{\text{EDM}}) \times \vec{S}, \\ \vec{\Omega}_{\text{MDM}} &= -\frac{q}{m\gamma} \left\{ (\gamma G + 1) \vec{B}_{\perp} + (G + 1) \vec{B}_{\parallel} - \left(\gamma G + \frac{\gamma}{\gamma + 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right\}, \\ \vec{\Omega}_{\text{EDM}} &= -\frac{q\eta}{2m} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} - \frac{\gamma}{\gamma + 1} \frac{\vec{\beta}}{c} (\vec{\beta} \cdot \vec{E}) \right), \end{aligned} \quad (1)$$

where $\vec{\Omega}_{\text{MDM}}$ and $\vec{\Omega}_{\text{EDM}}$ are the precession frequencies due to magnetic and electric dipole moments, respectively;

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$\vec{E}, \vec{B} = \vec{B}_\perp + \vec{B}_\parallel$ are the external magnetic and electric fields, respectively; m and q are the mass and charge of a particle; and γ is the Lorentz factor. The dimensionless η factor is connected to the EDM value d and the spin s of the particle: $d = \frac{\eta g}{2mc} s$, and $G = \frac{g-2}{2}$ is the anomalous magnetic moment.

For EDM measurements, it is first necessary to compensate for the MDM effect. The simplest approach, initially proposed at BNL [5], is based on the frozen spin method and uses an all-electric lattice, directly measuring spin precession due to a nonzero EDM in a radial electric field. This method requires the use of purely electric optical elements, and the lattice must be specifically designed for and operated with protons.

An alternative approach is the quasi-frozen spin concept, based on the idea of asynchronous spin precession compensation [6]. This leads to spin-vector oscillations back and forth relative to the momentum vector over one period and, as a result, over the full ring.

2.1 Relative spin motion in QFS

Let us introduce the QFS concept by examining orbital and spin rotation in a generalized framework. This approach is based on the dynamics governed by the Lorentz force for orbital motion and the T-BMT equation for spin precession. The foremost QFS condition that needs to be respected is that the orbital trajectory remains unperturbed, maintaining a closed orbit configuration.

$$\Phi_p^{\text{arc}} + \Phi_p^{\text{comp}} = \frac{2\pi}{N}, \quad (2)$$

where the index p stands for momentum, Φ_p^{arc} and Φ_p^{comp} are the total momentum rotations in the arcs and the spin compensator elements, respectively, and N is the lattice periodicity. To set up a lattice suitable for high-energy research, it is essential to employ a pure magnetic guiding field in the arc, given the limitations of achievable electric field strengths. Then, for a QFS lattice, a corresponding spin compensator should be implemented in the straight section without perturbing the orbit. The conditions that this device should satisfy can be formulated as $\Phi_p^{\text{arc}} = \frac{2\pi}{N}$ and $\Phi_p^{\text{comp}} = 0$. The second condition is met through employing both magnetic and electric fields. From Eq. 2, for a spin compensation element with both magnetic and electric fields:

$$\Phi_{pB}^{\text{comp}} + \Phi_{pE}^{\text{comp}} = 0, \quad (3)$$

where Φ_{pB}^{comp} and Φ_{pE}^{comp} are the total momentum rotations in the magnetic and electric fields at spin compensation. One can see from the T-BMT equation 1 that the electric field acts on spin with a maximum effectiveness when it is radial

to the momentum. Moreover, it is also maximally efficient with respect to the momentum rotation, which means

$$\vec{\Omega}_{pE}^{\text{max}} = \vec{\Omega}_{pE_\perp} = \frac{q}{m\gamma} \frac{\vec{\beta} \times \vec{E}_\perp}{c\beta^2}. \quad (4)$$

The second QFS condition that needs to be respected is to compensate for the MDM spin rotation in one period of the ring

$$\Phi_s^{\text{arc}} + \Phi_s^{\text{comp}} = 0, \quad (5)$$

where Φ_s^{arc} and Φ_s^{comp} are the total spin rotations in the arc and the spin compensator, respectively. The spin and orbital rotation angles (the Φ_s and Φ_p , respectively) are connected by the so-called spin tune ratio, given in the magnetic and electric fields as follows:

$$\nu_{B_\perp} = \gamma G, \quad \nu_E = \gamma \beta^2 \left(G - \frac{1}{\gamma^2 - 1} \right). \quad (6)$$

The spin tune difference is responsible for the compensation effect. In the pure magnetic arc, $\Phi_s^{\text{arc}} = \nu_{B_\perp} \Phi_p^{\text{arc}}$, while in the spin compensator, $\Phi_{sB}^{\text{comp}} = \nu_{B_\perp} \Phi_{pB}^{\text{comp}}$ and $\Phi_{sE}^{\text{comp}} = \nu_E \Phi_{pE}^{\text{comp}}$. Then Eq. 5 could be rewritten as

$$\begin{aligned} \nu_{B_\perp} \Phi_p^{\text{arc}} + \left(\nu_{B_\perp} \Phi_{pB}^{\text{comp}} + \nu_E \Phi_{pE}^{\text{comp}} \right) &= \\ &= \nu_{B_\perp} \left(\Phi_p^{\text{arc}} + \Phi_{pB}^{\text{comp}} \right) + \nu_E \Phi_{pE}^{\text{comp}} = 0. \end{aligned} \quad (7)$$

Finally, combining the first and second QFS conditions, the compensator electric and magnetic field spin rotation expressions can be obtained:

$$\Phi_{pE}^{\text{comp}} = -\Phi_{pB}^{\text{comp}} = \Phi_p^{\text{arc}} \frac{\gamma^2 G}{G+1} = \frac{2\pi}{N} \frac{\gamma^2 G}{G+1}. \quad (8)$$

Note that so far no mention was made of the physical structure of the compensation element, only of the integral features of the presented field components.

2.2 Spin compensation element length

The spin compensation element length can be calculated as follows

$$L = \Phi_{pB}^{\text{comp}} R_B = \Phi_{pE}^{\text{comp}} R_E, \quad (9)$$

where R_B, R_E are the radii of the magnetic and electric fields, respectively. In general, the net curvature of an element with combined magnetic and electric fields is

$$\frac{1}{R} = \frac{1}{R_B} + \frac{1}{R_E}, \quad R_B = \frac{B\rho}{B}, \quad R_E = \frac{\kappa}{E}, \quad (10)$$

where $B\rho = \frac{p_0}{e}$ is the magnetic rigidity, $p_0 = \gamma m\beta c$ and $\kappa = \frac{p_0\beta c}{e}$ is the electrical rigidity. Because the element must satisfy the zero net orbital distortion condition, the net Lorentz force must vanish. Therefore, the net curvature is zero, i.e., $1/R = 0$, which leads to $R_B = -R_E$. The electric field strength limitation is considerably more stringent than that of the magnetic field. The compensator length per period can be obtained using Eqs. 8 and 9:

$$\begin{aligned} L_{\min} = \Phi_{pE}^{\text{comp}} R_E &= \frac{2\pi}{N} \frac{\gamma^2 G}{G+1} \frac{\kappa}{E_{\max}} = \\ &= \frac{2\pi}{N} \frac{G}{G+1} \frac{mc^2}{e} \frac{\gamma(\gamma^2 - 1)}{E_{\max}}, \end{aligned} \quad (11)$$

where $E_{\max}$ is the maximum electric field, which limits the minimal achievable length regardless of the researched particle. The total length $L = L_{\min}^{\text{total}} = N \cdot L_{\min}$ is independent of the number of periods. Maximum attainable electric fields are 10–13 MV/m [7], which corresponds to a magnetic field of the order of 70–90 mT, accordingly. This will be used later for evaluation.

3 Features of deuteron and proton

3.1 Dependence on beam parameters

The first thing that needs to be accounted for in an efficient analysis of the spin dynamics is the polarimeter analyzing power. It depends on the beam energy and has to be maximal to achieve sufficient statistics. The maximum figure of merit of the polarimeter is reached at a proton beam energy of 270 MeV [8], and the same is true for deuterons [9].

Orbital and spin dynamics vary among different types of particles. In the first place, the deuteron mass-to-charge ratio is twice that of the proton. In the second place, the anomalous magnetic moments are notably different: for the proton, $G_p = 1.79$, and for the deuterons, $G_d = -0.14$. These differences, gathered in Table 1, call for a tailored approach to each particle type when designing experiments as well as when analyzing results.

In a magnetic field, according to Eq. 6, the direction of spin precession depends solely on the sign of the anomalous magnetic moment—i.e., it is independent of energy.

Table 1 Particles and experiment parameters

Particle	A/Z	G	γ_{exp}	E_{exp} (MeV/u)	L (m)
Deuteron, d	2	-0.14	1.144	135	53
Proton, p	1	1.79	1.289	270	247
			1.078	73	53

However, the magnitude is influenced by both energy and the absolute value of the anomalous magnetic moment. For protons, this effect is so important that care must be taken to ensure that the condition for spin-vector rotation per arc, $\gamma G \cdot \Phi_p^{\text{arc}} < \pi/2$, is satisfied in order to preserve the accumulation of the EDM effect for the longitudinally polarized beam. This implies that QFS lattices only with a periodicity $N = 8$ or larger provide the means to measure the proton EDM.

To be more precise, an EDM measurement under QFS conditions is attenuated relative to a frozen spin measurement. To first order, the attenuation factor is given by [10]

$$J_0(\Phi_s^{\text{arc}}) = 1 - \frac{\Phi_s^{\text{arc}2}}{4}, \quad (12)$$

where Φ_s^{arc} represents the angle associated with the MDM effect in the arc in one period. For various particle types and structure periodicities, the attenuation factor is cited in Table 2. The maximum periodicity considered is $N = 16$, due to lattice design limitations. The table shows that the frozen and quasi-frozen spin regimes are practically the same for deuterons. For protons, only the 16-periodic lattice offers a real opportunity for practical tests of the QFS approach.

In electrostatic fields, the analysis of deuteron and proton behaviors is further complicated by their distinct interactions with the field. For protons, the direction of spin rotation can depend on the energy, particularly around the “magic” energy, where $\gamma_{\text{mag}} = \sqrt{\frac{G_p+1}{G_p}} = 1.248$ ($E_{\text{mag}} = 233$ MeV).

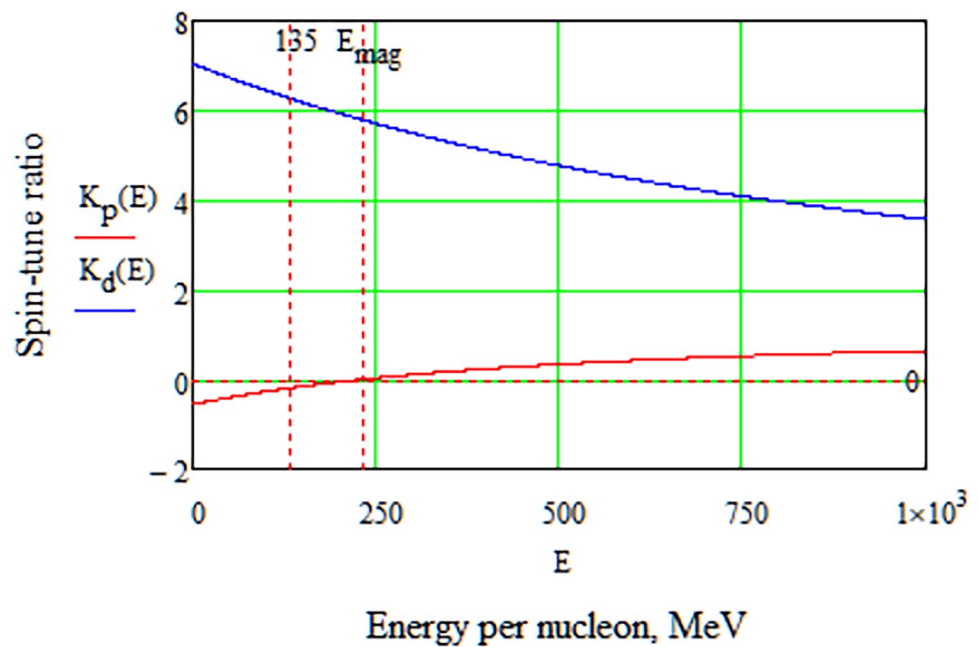
Nevertheless, the influence on protons is much lower than for deuterons, as shown in Fig. 1. For deuterons, on the other hand, there is no equivalent “magic” energy, and their spin rotation behavior remains consistent across the entire energy range.

These fundamental differences lead to several important consequences for lattice construction. Specifically, modifications are necessary to accommodate both particle types. First, according to Eq. 8, the direction of spin rotation differs between protons and deuterons. This necessitates either

Table 2 Parameters of lattices and experiment at beam energy of 270 MeV

Particle	N	Φ_s^{arc} (deg)	$J_0(\Phi_s^{\text{arc}})$
Deuteron d	2	-29.45	0.934
	4	-14.72	0.983
	8	-7.36	0.996
	16	-3.68	0.999
Proton p	8	103.83	0.179
	16	51.91	0.795

Fig. 1 Spin tune ratio $K = \frac{\nu_{B\perp}}{\nu_E}$ for deuteron and proton. (Color figure online)

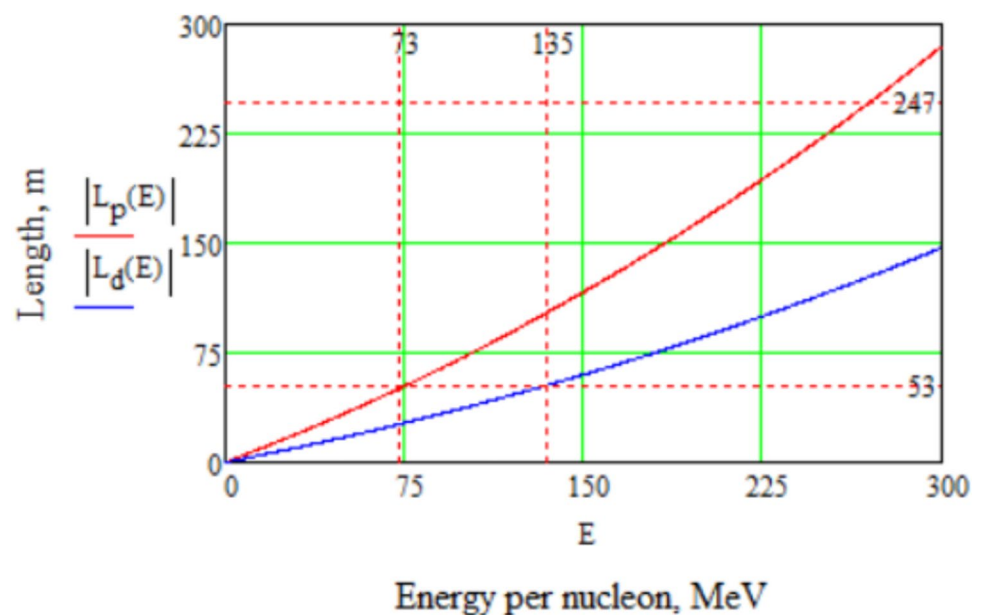


switching the polarity of the spin compensator's fields or rotating it by π along the longitudinal axis. Second, the minimal achievable spin compensator length, as given by Eq. 11, is longer for protons than for deuterons at the optimal polarimeter energy. This discrepancy can be addressed by lowering the experimental energy for protons (Fig. 2). At a spin compensator length equivalent to that used for deuterons, the proton energy should be reduced to 73 MeV, and the analyzing power decreases by a factor of 2–3. Third, two viable approaches for arranging additional EM fields are the implementation of a Wien filter or an electrostatic deflector with a kicker.

3.2 Wien filter

The Wien filter serves an important function in a particle accelerator, designed to manipulate spin dynamics without altering the orbital trajectory of particles by utilizing perpendicular electric and magnetic fields that cancel each other out, resulting in zero net Lorentz force. As the EDM T-BMT term is proportional to the Lorentz force, the Wien filter will not exert an EDM force on the spin vector. It is EDM-transparent. It allows particles to move in a straight line while enabling a precise correction of their spin orientations, making it an ideal auxiliary device for experiments requiring

Fig. 2 Total length of spin compensator vs. energy per nucleon required to achieve QFS lattice for deuteron and proton. (Color figure online)



spin manipulation. It provides the conditions to facilitate spin navigation. The filter's design ensures a net absence of deflection along the beamline, minimizing additional space requirements in the ring's straight sections and allowing for a classical sequential arrangement of ring elements.

It is evidently usable for both deuterons and protons; for deuterons, it can be employed directly at optimal energies, while for protons, the polarity must be switched or the setup rotated by π along the longitudinal axis and used at lower energies (Fig. 3). This flexibility allows for freedom in developing methods for studying spin dynamics across different particle types. Overall, the Wien filter's ability to control particle spin without perturbing orbital paths makes it an invaluable component in advanced accelerator experiments.

3.3 Electrostatic deflector with kicker

The pure electrostatic deflector is designed to manipulate particle trajectories and spin dynamics by creating a radial electric field with a nonzero curvature. Unlike the Wien filter, this deflector requires an additional kicker to compensate for orbital deviations, which increases the overall length of the compensator. This setup is particularly useful for creating bypass sections in addition to the native straight sections, allowing for flexible experimental configurations (Fig. 4). However, the distance between the spatial assignment of equipment should be considered to enable the option

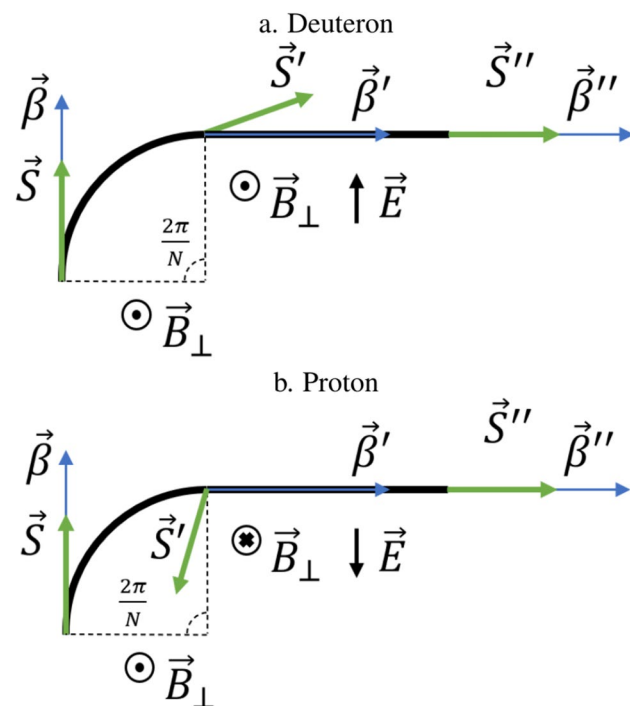


Fig. 3 One period conceptual scheme of QFS lattice with Wien filters for (a) deuterons, (b) protons. (Color figure online)

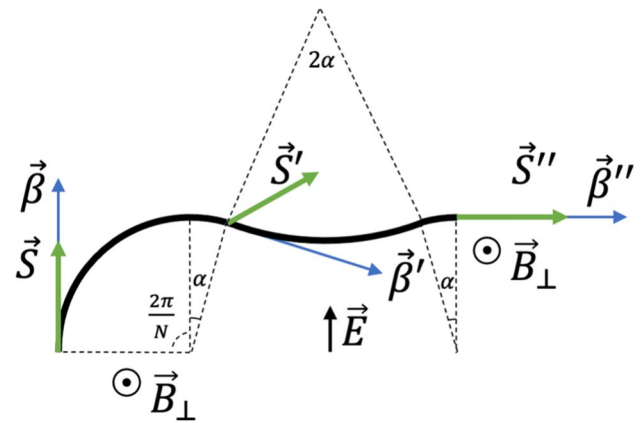


Fig. 4 One period conceptual scheme of QFS lattice with electrostatic deflector and kicker for deuterons. (Color figure online)

with an independent section. A key challenge is that each type of particle requires a different curvature, which must be determined at the outset of lattice design. Despite these complexities, the electrostatic deflector with kicker offers a robust solution for controlling particle spin and trajectory.

4 Further research

Currently, the proposed energy requirements for EDM studies are set at 270 MeV and lower, but specific conclusions regarding the arc spin rotation have yet to be drawn. The primary condition is to achieve a momentum rotation at a specific angle Φ_p^{arc} with a corresponding Φ_s^{arc} for the spin. This can be accomplished by carefully selecting the magnetic field integral to ensure precise alignment of momentum and spin dynamics. To maximize efficiency, the magnetic field should be as strong as possible to minimize the effective arc length, in consideration of the unique features of the lattice design. This approach not only optimizes studies at the current energy range but also opens the possibility for other polarized or non-polarized beam research at higher energies, potentially reaching several GeV. The versatility of the QFS setup allows it to be implemented in various lattice designs, including existing accelerator rings, thereby facilitating advanced studies at elevated energy ranges.

Wien filters do not affect beam dynamics and influence only the spin motion. This helps in converting the storage ring into a broadband axion antenna [11, 12].

5 Summary

This article presents the implementation of a quasi-frozen spin setup in a periodic lattice to study the electric dipole moments of charged light particles. The design achieves

precise spin compensation of the MDM effect per one period by employing elements with matched curvatures for electric and magnetic fields, allowing for effective spin manipulation. Either Wien filters, which do not cause beam deflection, or electrostatic deflectors, which enable bypass creation, are imperative to the flexibility of this concept. An expression for the optimal spin compensator length is derived. Notably, the setup allows for the investigation of the proton EDM using the same ring as for deuterons, simply by switching the polarity or rotating the spin compensator by π and operating at a reduced energy. The study demonstrates the versatility of the quasi-frozen spin lattice, which can be adapted for multiple purposes, including higher-energy research within existing facilities and axion-like particle searches.

Author contributions All authors contributed to the study conception and design. Material preparation and analysis were performed by S. Kolokolchikov. The first draft of the manuscript was written by S. Kolokolchikov, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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