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Implementation of the frozen-spin technique for the search for a muon electric dipole moment

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Abstract: Applying the frozen-spin technique in a compact 3 T solenoid will enable a search for the muon electric dipole moment (EDM) with unprecedented sensitivity, improving upon the current direct limit by approximately a factor of 1000. After injection of a selected muon, a pulsed magnetic field will reduce its longitudinal momentum sufficiently to be confined within a static weakly-focusing magnetic field and maintain a closed circular orbit. A precisely tuned radial electric field will cancel the spin precession induced by the muon's anomalous magnetic moment, $a = (g - 2)/2$, relative to the orientation of the momentum. In this configuration, the EDM becomes the only remaining inherent source of relative precession. Asymmetry in the direction and energy of positrons emitted from muon decay provides an experimental signature of such precession.

In the first of two phases, 28 MeV/c muons from the $\pi E1$ beamline at PSI will be used to demonstrate the systems necessary for injecting and trapping muons, tuning fields to the frozen-spin condition and reconstructing positron trajectories. Designs for the coils producing the pulsed magnetic field and the electrodes applying the frozen-spin electric field are currently being evaluated with simulations and prototypes. These systems must be designed in parallel, especially due to the impact of eddy-currents induced in the electrodes by the pulsed magnetic field. The electrode design must minimise eddy-currents to preserve the field strength of the pulsed field responsible for muon trapping, while maintaining the electric field uniformity necessary to achieve the sensitivity goal. This article summarises some of the efforts underway to address these design challenges.

Keywords: Detector design and construction technologies and materials; Low-energy ion storage

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2024 JINST 19 P01021

Contents

1 Introduction

Many searches for new physics pursue signatures of enhanced CP violation which may inform Standard Model extensions. The EDM of an elementary particle is a yet-unobserved CP-violating phenomenon. The largest Standard Model prediction in literature for the muon is $d_\mu = 1.4 \times 10^{-38}\, e \cdot \mathrm{cm}$ [1], well below the current experimental limit $d_\mu < 1.8 \times 10^{-19}\, e \cdot \mathrm{cm}$ (95% C.L.) [2]. The electron EDM limit has advanced considerably further in recent decades to $d_e < 4.1 \times 10^{-30}\, e \cdot \mathrm{cm}$ (90% C.L.) [3]. Assuming lepton flavour universality, d_μ may be indirectly constrained by a mass scaling of d_e. However, a direct search is able to probe new physics relaxing this assumption.

The frozen-spin technique [4] will be employed, for the first time, in a direct search for the muon EDM at the Paul Scherrer Institute (PSI) [5]. The difference between the spin precession frequency $\vec{\Omega}_0$ and the cyclotron frequency $\vec{\Omega}_c$ for a particle of charge-to-mass ratio q/m with velocity $\vec{\beta}$ in the presence of electric ($\vec{E}$) and magnetic ($\vec{B}$) fields is given by [6]

$$\begin{aligned}\vec{\Omega} = \vec{\Omega}_0 - \vec{\Omega}_c = \frac{-aq}{m}\left(\vec{B} - \frac{\gamma}{\gamma+1}(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(1 + \frac{1}{a(1-\gamma^2)}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right) \\ - \frac{\eta q}{2m}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c} - \frac{\gamma}{c(\gamma+1)}(\vec{\beta}\cdot\vec{E})\vec{\beta}\right)\end{aligned} \tag{1.1}$$

for $a = (g-2)/2$ the anomalous magnetic moment and η the EDM strength, where $\vec{d} = \eta\frac{e}{2mc}\vec{s}$. The red terms vanish for $\vec{B}$, $\vec{E}$, and $\vec{\beta}$ mutually orthogonal. In the frozen-spin technique, the blue terms cancel for a longitudinal field $\vec{B} = B_z\hat{z}$ and radial field $\vec{E} = E_\rho\hat{\rho}$ tuned to $E_f \approx aB_z\beta c\gamma^2$ where $\vec{\beta} = \beta\hat{\phi}$ is the purely azimuthal velocity of the nominal orbit. Under this condition, the spin is *frozen* to the momentum in the absence of an EDM. For η nonzero, the remaining terms in eq. 1.1 induce spin precession about $\hat{\rho}$. The direction and energy of positrons emitted from decays are sensitive to the muon spin phase [7], offering an experimental signature of EDM-induced spin precession.

2 Muon storage pulse

Upon injection into a 3 T solenoid, a trigger signal will be generated by an entrance detector to select muons within the storage phase space. As the muons approach the centre of the solenoid ($z = 0$), a storage pulse will be generated by a pair of single-loop circular coils with counter-flowing current (anti-Helmholtz configuration) supplied by a purpose-built pulse generator. The radial component of this pulsed magnetic field will transfer longitudinal into transverse momentum. A single-loop coil at $z = 0$ will produce a static weakly-focusing field defining the storage region. It will provide longitudinal confinement sufficient to store muons with some remaining longitudinal momentum.

The longitudinal momentum is initially defined by the injection angle, but reduces substantially along the spiral due to the radial component of the solenoid field. The strength of the pulsed field required to kick a given longitudinal momentum p_z can be estimated by solving the differential equation given by the Lorentz force,

$$\dot{\vec{p}}(t) = \frac{e}{\gamma m} \vec{p} \times \vec{B}_{\text{pulse}}(t) \implies \dot{p}_z(t) = \frac{e}{\gamma m} p_\phi \vec{B}_{\text{pulse}}(t) \cdot \hat{\rho} \tag{2.1}$$

for p_ϕ the transverse momentum and $\hat{\rho}$ the radial unit vector perpendicular to $\hat{z}$. Assuming a half-sine pulse shape of full width w and peak amplitude B_{max} (such that $\vec{B}_{\text{pulse}}(t) \cdot \hat{\rho} = B_{\text{max}} \sin(\pi t/w)$ for $0 \leq t \leq w$), the pulse integral ($2wB_{\text{max}}/\pi$) necessary to fully kick the muon ($p_z \to 0$) scales linearly (where $p_z \ll p$) with the initial value of p_z. The gradient in this linear regime is $43\,\text{mTns}/(\text{MeV}/c)$. Given the proposed design, we can consider a pulse of width $w = 50\,\text{ns}$ and peak (radial) amplitude $B_{\text{max}} = 1\,\text{mT}$. In this half-sine approximation, this gives $32\,\text{mTns}$ corresponding to a kick of $0.75\,\text{MeV}/c$ and a traversed longitudinal distance of 53 mm. Numerical simulations, incorporating a field map generated in Ansys [8], show that the half-sine approximation is a reasonable description of the field seen by the muon when the separation of the coils is comparable to their radii. The parameter ranges are also validated by ongoing holistic simulations [9] using G4Beamline [10].

In the design, a suitable choice of injection angle will ensure that the remaining longitudinal momentum upon approach to the storage region $p_z(0)$ matches the applied kick. The distance separating the pulse coils will be configured such that muons with the nominal $p_z(0)$ are stored at their midpoint ($z = 0$), ensuring longitudinal oscillations in the weakly-focusing field are minimised. In this case, the applied kick must be increased by an offset corresponding to the momentum imparted by the weakly-focusing field upon approach. During the experiment, fine tuning of the pulse current will enable precise matching to optimise muon storage efficiency.

To produce the $\sim 1\,\text{mT}$ radial field strength at the nominal orbit radius, the pulse generator will be designed to deliver a peak current of up to 200 A. The pulse shape depends on the reactance of the entire circuit, including the pulse coils, supply lines, and inductive couplings. Achieving the desired pulse width $\sim 50\,\text{ns}$ relies on minimising and precisely measuring the inductance. Prototypes of single-loop copper coils with outer radius 50 mm and square cross-section $10 \times 10\,\text{mm}^2$ give a measured inductance of 121(1) nH. The total load inductance can be reduced by running parallel supply cables, calibrated to ensure pulse synchronisation. Another essential constraint for the pulse generator is its latency. Using precise field maps obtained from measurements of the solenoid, we estimate the muon passage to be $\sim 105\,\text{ns}$ from injection to arrival at the storage region. Accounting for trigger signal processing and transmission delays, the latency must be $\leq 60\,\text{ns}$.

Once muons are trapped with their spin frozen, the experiment becomes sensitive to EDM-induced precession. Therefore the pulse tail must be short and after-pulse oscillations suppressed to avoid extraneous time-varying radial magnetic fields that could produce an EDM-like signal. Consideration of systematic effects shows that a slowly-varying field of 20 μT would introduce an EDM-like precession equivalent to the Phase I sensitivity goal, $\sigma(d_\mu) < 3 \times 10^{-21}\,e\cdot\text{cm}$. Since the pulse coils modelled in Ansys supply $\sim 10\,\mu\text{T/A}$ at the orbit radius, an upper limit of 1 A is a suitable constraint on after-pulse oscillations.

3 Frozen-spin electric field

The radial electric field will be applied by concentric cylindrical electrodes enclosing the muon orbit. The outer electrode ($r = 40$ mm) will be grounded and an inner electrode ($r = 20$ mm) at a high voltage (HV) of approximately 6 kV such that the required $E_f \approx 3$ kV/cm is present at the nominal orbit radius ($\rho = 31$ mm). As shown in section 1, E_f scales linearly with the velocity β, which is distributed according to a momentum bite $\Delta p/p_0 = 0.5\%$ defined by the incoming beam tuned to mean momentum p_0. Muons with higher momentum will orbit with a correspondingly larger radius and thus experience a lower field due to the radial dependence of the field. The higher momentum, however, would actually necessitate a higher field strength to satisfy the frozen-spin condition. This effect limits the matching of the frozen-spin field strength to approximately 1% over the momentum distribution, and thus a relative precision better than $\sim 0.5\%$ on the applied voltage, corresponding to 30 V, is sufficient. To avoid systematic effects in the observed asymmetry [11], the stability of this applied voltage over time must be carefully constrained. Both requirements can be realised using commercially available high voltage amplifers.

If the frozen-spin condition is not satisfied, due to a radial field $E_\rho = E_f + E_{\text{offset}}$, the spin will precess in the plane of the orbit with frequency

$$\omega_a = \frac{-ae}{m} B_z \frac{E_{\text{offset}}}{E_f} \tag{3.1}$$

due to the AMM-induced precession, described by the terms proportional to a in eq. 1.1. This can be measured through the transverse asymmetry of emitted positrons (in contrast to the longitudinal asymmetry for an EDM signal). By scanning the electric field above and below E_f, an interpolation to $\omega_a = 0$ will verify whether the applied voltage supplies the necessary field strength to satisfy the frozen-spin condition for the actual ensemble of stored muons.

The electrodes must be thin to minimise multiple scattering of decay positrons. The material must be mechanically robust to maintain surface homogeneity and concentric alignment. This is essential to minimise non-uniformities that could perturb the muon orbit or deviate from the frozen-spin condition [11]. The longitudinal component of the electric field must be limited to control systematic effects [11]. Prototype electrodes made from aluminised Kapton films (30 nm Al on 25 µm Kapton) are currently being used to study eddy-currents induced by the muon storage pulse. This effect can be reduced by using material of higher resistivity or modifying the geometry. The radial component of the magnetic field at the muon orbit must therefore be measured to determine the shielding and inform design optimisation. Using a pickup coil of 5 mm radius, the voltages induced by a 10 MHz sinusoidal current in the pulse coils for various electrode configurations have been compared to the nominal field observed at the radius of the muon orbit and centred between the pulse coils (separated by 100 mm). A ground electrode made from homogeneously aluminised Kapton gave a maximum (opposite the gluing seam) shielding factor of 1.9(1), which increased to 3.0(2) with the addition of the HV electrode, and suffered an azimuthal asymmetry due to the discontinuity at the gluing seam. A new prototype has been prepared with the aluminium coating distributed in 2 mm stripes (pitch 2.2 mm), for which the induced voltage was indistinguishable within experimental sensitivity from the reference, such that the shielding factor was less than 1.1 (90% C.L.). This pattern avoids the azimuthal asymmetry and prevents radial eddy-current flow across length scales comparable to the coils, permitting near-complete field transmission.

4 Outlook

Prototypes of the pulse coils, responsible for muon trapping, are being tested to provide input for the design of a purpose-built pulse generator. In particular, the inductance of the pulse coils defines the shape of the current pulse and informs R&D towards a purpose-built pulse generator. To reduce the material budget, we are exploring coils constructed from copper sheets which provide comparable inductance and resistance at high frequencies due to the skin effect. Achieving the frozen-spin condition also relies on precise tuning and alignment of the radial electric field. Electrode prototypes have been prepared to study their shielding effect on the magnetic field at the muon orbit. This informed the development of a segmented electrode to suppress eddy-current flow. Measurements of surface uniformity and alignment are underway to characterise expected systematic effects.

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2024 JINST 19 P01021