SPIN TRACKING SIMULATIONS TOWARDS ELECTRIC DIPOLE MOMENT MEASUREMENTS AT COSY

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Abstract
A strong hint for physics beyond the Standard Model would be achieved by direct measurements of charged particles’ Electric Dipole Moments (EDMs). Measurements in magnetic storage rings using a resonant spin interaction of a radiofrequency Wien filter are proposed and needs to be scrutinized. Therefore, the calculation of phase space transfer maps for time-varying fields has been implemented into an extension for the software framework COSY INFINITY. Benchmarking with measured data and analytical estimates for rf solenoid induced spin resonances are in good agreement. The dependence of polarization oscillation damping on the solenoid frequency could be confirmed. First studies of the rf Wien filter method reveal systematic limitations: Incorrect Gaussian distributed misalignments of the COSY lattice quadrupoles with a standard deviation of σ = 0.1 mm generate a similar buildup as an EDM d ≈ 5 ⋅ 10⁻¹⁹ e ⋅ cm using this method.

INTRODUCTION
The JEDI collaboration investigates the feasibility of electric dipole moment (EDM) measurements of protons and deuterons in storage rings. Methods requiring radiofrequency fields to create an EDM related measurement signal in a magnetic storage ring like COSY [1] are proposed [2, 3]. Systematic tracking studies need to be performed to explore the limits of these methods. This requires the fast tracking of particles in radiofrequency fields in presence of an EDM. The software framework COSY INFINITY [4] is used to calculate transfer maps of the magnetic elements and perform tracking. Recent efforts extend the code by the EDM contribution and by calculation of maps for time-varying fields. Benchmarking of the new algorithms using measured data and analytical estimations is carried out. Based on the results systematic limitations of the measurement methods can be deduced.

BENCHMARKING USING AN RF SOLENOID INDUCED SPIN RESONANCE
First benchmarking is performed using calculations and measurements for an rf-B solenoidal field on the COSY. Preceding studies of this process can be found in [5]. For these studies a vector polarized deuteron beam was injected, electron cooled and accelerated up to p = 970 MeV/c.

\[
B_{\text{sol}} = B_{\text{sol}} \cos(2\pi v_{\text{sol}} + \phi_{\text{sol}}). 
\]  

The spin tune for the particular setup is νs ≈ Gγ ≈ −0.16 [7], where G is the anomalous magnetic moment. The spin resonance condition for the solenoidal field is given by

\[
\nu_{\text{sol}} = \nu_s + K, \quad K \in \mathbb{Z}. 
\]  

Analytical estimations predict a vertical polarization Pν(ν) oscillation, which depends on the harmonic number K:

\[
P_{\nu}(\nu) = \int_{-\infty}^{\infty} \rho(\nu) S_{\nu}(\nu, \hat{\nu}) d\nu, 
\]

\[
S_{\nu}(\nu, \hat{\nu}) = \cos\left(\frac{\alpha_0}{2} J_0(C \cdot \hat{\nu}) \cdot \nu\right), 
\]

\[
\alpha_0 = (1 + G) \frac{q}{\mu} \left(\hat{B} \cdot L\right)_{\text{sol}}, 
\]

\[
C = \omega_{\text{rev}} \nu_{\text{sol}} - \frac{G\gamma \beta^2}{\eta_{\text{ts}}}. 
\]

Here, Sν denotes the vertical spin component, \((\hat{B} \cdot L)_{\text{sol}}\) denotes the field amplitude times the length of the solenoid,

4: Hadron Accelerators
A23 - Accelerators and Storage Rings, Other
\( \omega_{\text{rev}} \) defines the revolution frequency and \( \eta_{\text{sl}} \) is the time slip factor. The longitudinal amplitude distribution \( \rho(\hat{\tau}) \) of the bunch can be extracted from the counted events as follows. Assuming a probability of presence of an harmonic oscillator the longitudinal time offset \( \tau \) with respect to the bunch center can be characterized by:

\[
\tau = \hat{\tau} \cdot \cos(2\pi \nu_{\text{sync}} \cdot n + \phi)
\]

for a single particle. Accumulation of all events in a slice of three million turns, before the solenoid is turned on, results in the \( \tau \)-distribution shown in Fig. 2. The bunch center is determined by the mean value of a Gaussian fit. The amplitude distribution \( \hat{\tau} \) is derived by deconvolution of the measured distribution assuming Eq. 7. Tracking of the \( \tau \)-coordinate for 700 particles initially distributed according to the \( \hat{\tau} \)-distribution results in the slightly smaller overlayed distribution of Fig. 2. For further comparison with measured data, the deconvolved distribution has been approximated by a sum of Gauss functions and slightly broadened. The Bessel function \( J_0 \) in Eq. 4 has been expanded to second order of its argument. Figure 3 shows the vertical polarization oscillations for different solenoidal tunes \( \nu_{\text{sol}} \). The amplitude and the parameter \( \alpha_0 \) are determined by a fit, while \( \eta_{\text{sl}} \) is extracted from lattice calculations. These parameters are further used to setup the tracking simulations for different values of \( \nu_{\text{sol}} \). Measurements, analytical estimations as well as tracking results are in good agreement with each other and confirm the \( \nu_{\text{sol}} \)-dependence of the driven polarization oscillations.

**SYSTEMATIC LIMITATIONS OF RADIOFREQUENCY EDM METHODS**

Proposed radiofrequency EDM methods are also based on induced spin resonances, but the polarization oscillation frequency depends on the EDM magnitude. An rf-ExB Wien filter with vertical magnetic field is planned to be used to induce this kind of resonance [2, 3]. The buildup for the closed orbit particles can be approximated up to first order yielding

\[
\frac{\text{d}S_x}{\text{d}n} = - \frac{\alpha_0}{2} \left( n_y^2 - n_z \cdot \sin(\phi_{\text{WF}}) + n_y \cdot n_x \cdot \cos(\phi_{\text{WF}}) \right) + \text{fast osc. terms,}
\]

\[
\alpha_0 = \frac{1 + G \frac{q}{p} (\hat{B} \cdot L)_{\text{WF}}}{\gamma},
\]

\[
B_{\text{WF}}(n) = \hat{B}_{\text{WF}} \cos(2\pi \nu_{\text{WF}} + \phi_{\text{WF}}),
\]

\[
E_{\text{WF}}(n) = \beta c \cdot B_{\text{WF}}(n), \quad (\hat{E}_{\text{WF}} + \beta c \times \hat{B}_{\text{WF}} = \vec{0})
\]

for an initial longitudinal spin vector at the rf Wien filter location \( \vec{S}_z(0) = 1 \). The spin closed orbit of the static ring at the rf Wien filter location is given by \((n_x, n_y, n_z)\). In an ideal ring and without EDM it points parallel to the vertical guiding field. A non-vanishing EDM introduces a \( n_x \) component, while magnet misalignments might as well introduce a \( n_z \) component. Figure 4 illustrates the buildup for an EDM with \( \eta = 5 \times 10^{-5} \) \((d = \eta \frac{q^2}{2mc} \approx 5 \cdot 10^{-20} \text{ e cm})\) with and without randomized quadrupole misalignments. According to Eq. 8 the buildup depends on the initial phase
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REFERENCES