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 extensions 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: Uncorrected Gaussian distributed misalignments of the COSY lattice quadrupoles with a standard deviation of $\sigma = 0.1$ mm generate a similar buildup as an EDM $d \approx 5 \cdot 10^{-19}\,\mathrm{e} \cdot \mathrm{cm}$ 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 needs 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 solenoid induced spin resonance at 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 $p = 970\,\mathrm{MeV/c}$.
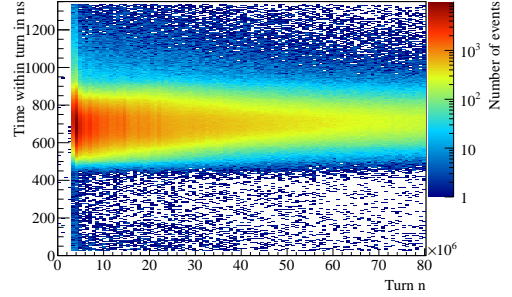
Figure 1: Event distribution within a turn vs. turn number for one measurement cycle.

The revolution time was roughly $T = 1332$ ns. After electron cooling had been turned off, a white noise electric signal was used to slowly extract the deuters onto a carbon block target of the internal polarimeter. The scattering events were counted in four quadrants (up, down, left, right). The left-right-asymmetry is proportional to the vertical polarization. A more detailed description of the setup has been discussed in [6, 7]. Figure 1 shows the event distribution during one measurement cycle. The timemarking system of the read-out electronics [6] allows to determine the event time with respect to the rf cavity period. The zero point is set to be shortly before the extraction starts. After about eleven million turns the rf-B solenoidal field was turned on:

$$B_{\mathrm{sol}} = \hat{B}_{\mathrm{sol}} \cos(2\pi \nu_{\mathrm{sol}} + \phi_{\mathrm{sol}}). \qquad (1)$$

The spin tune for the particular setup is $\nu_s \approx G\gamma \approx -0.16$ [7], where G is the anomalous magnetic moment. The spin resonance condition for the solenoidal field is given by

$$\nu_{\mathrm{sol}} = \nu_s + K, \quad K \in \mathbb{Z}. \qquad (2)$$

Analytical estimations predict a vertical polarization $P_y(n)$ oscillation, which depends on the harmonic number K:

$$P_y(n) = \int_{-\infty}^{\infty} \rho(\hat{\tau}) S_y(n, \hat{\tau}) d\hat{\tau}, \qquad (3)$$

$$S_y(n, \hat{\tau}) = \cos\left(\frac{\alpha_0}{2} \cdot J_0(C \cdot \hat{\tau}) \cdot n\right), \qquad (4)$$

$$\alpha_0 = (1 + G)\frac{q}{p}\left(\hat{B} \cdot L\right)_{\mathrm{sol}}, \qquad (5)$$

$$C = \omega_{\mathrm{rev}}\left(\nu_{\mathrm{sol}} - \frac{G\gamma\beta^2}{\eta_{\mathrm{ts}}}\right). \qquad (6)$$

Here, S_y denotes the vertical spin component, $\left(\hat{B} \cdot L\right)_{\mathrm{sol}}$ denotes the field amplitude times the length of the solenoid,
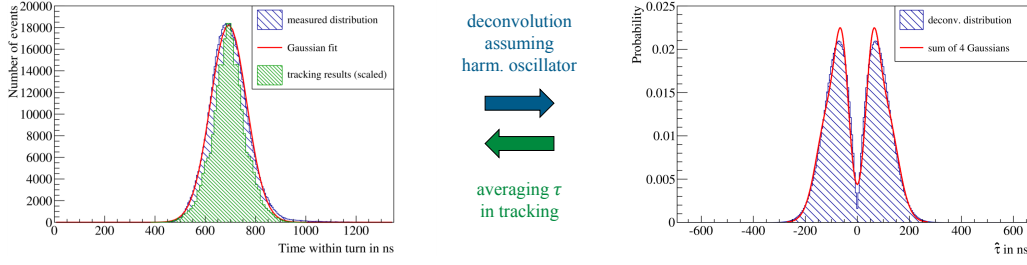
Figure 2: The left distribution shows the accumulated events for 3 mio. turns before the solenoid was turned on (see also Fig. 1). The distribution was fitted by a Gaussian and deconvolved to derive the initial longitudinal amplitude $\hat{\tau}$-distribution (right). The $\hat{\tau}$-distribution was approximated by a sum of four Gaussians. 700 particles were generated according to the $\hat{\tau}$ distribution and tracked for 50 000 turns. This results in the overlayed distribution (left).
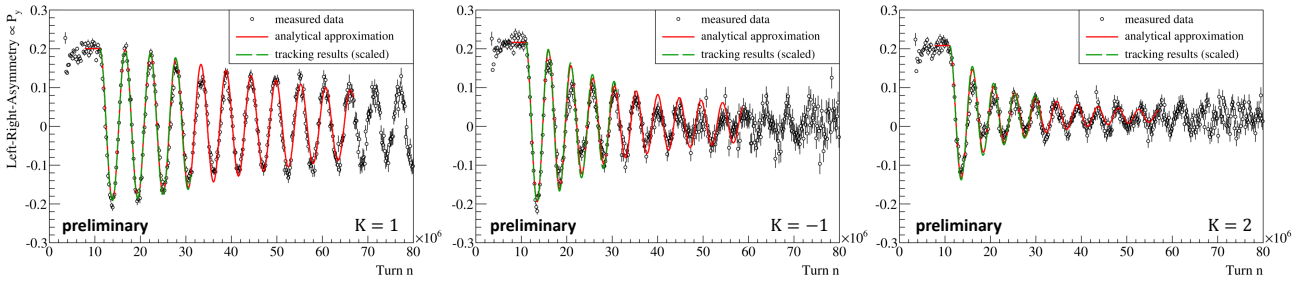

Figure 3: Induced vertical polarization by a rf solenoid driven spin resonance. The three cases correspond to nearly the same solenoidal magnetic field, but different excitation frequencies as defined in Eq. 2.

ω_{rev} defines the revolution frequency and η_{ts} 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 τ with respect to the bunch center can be characterized by:

$$\tau = \hat{\tau} \cdot \cos(2\pi\nu_{\mathrm{sync}} \cdot n + \phi) \tag{7}$$

for a single particle. Accumulation of all events in a slice of three million turns, before the solenoid is turned on, results in the τ-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 τ-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 ν_{sol}. The amplitude and the parameter α_0 are determined by a fit, while η_{ts} is extracted from lattice calculations. These parameters are further used to setup the tracking simulations for different values of ν_{sol}. Measurements, analytical estimations as well as tracking results are in good agreement with each other and confirm the ν_{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-E×B 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

$$\frac{\mathrm{d}S_y}{\mathrm{d}n} = -\frac{\alpha_0}{2}\left(n_y^2 \cdot n_z \cdot \sin(\phi_{\mathrm{WF}}) + n_y \cdot n_x \cdot \cos(\phi_{\mathrm{WF}})\right)$$
$$+ \text{ fast osc. terms,} \tag{8}$$

$$\alpha_0 = \frac{1+G}{\gamma}\frac{q}{p}\left(\hat{B}\cdot L\right)_{\mathrm{WF}}, \tag{9}$$

$$B_{\mathrm{WF}}(n) = \hat{B}_{\mathrm{WF}}\cos(2\pi\nu_{\mathrm{WF}} + \phi_{\mathrm{WF}}), \tag{10}$$

$$E_{\mathrm{WF}}(n) = \beta c \cdot B_{\mathrm{WF}}(n), \quad \left(\vec{E}_{\mathrm{WF}} + \vec{\beta}c \times \vec{B}_{\mathrm{WF}} = \vec{0}\right) \tag{11}$$

for an initial longitudinal spin vector at the rf Wien filter location $S_z(0) = 1$. 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 $\eta = 10^{-5}$ ($d = \eta\frac{q\hbar}{2mc} \approx 5\cdot10^{-20}\,\mathrm{e}\cdot\mathrm{cm}$) with and without randomized quadrupole misalignments. According to Eq. 8 the buildup depends on the initial phase
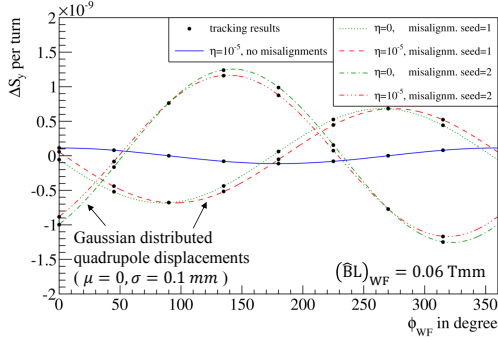
Figure 4: Vertical spin buildup for closed orbit deuterons in an ideal ring, as well as for quadrupole misalignments for two different randomization seeds. The black dots show tracking results, the colored lines are analytical estimates.
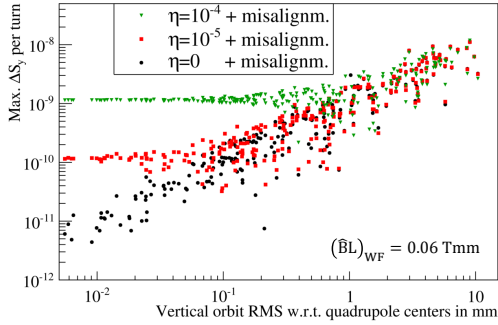

Figure 5: Maximum vertical spin buildup per turn for different EDM magnitudes and Gaussian distributed quadrupole shifts with different standard deviations. The RMS value of the vertical orbit displacement is used as a measure for misalignments.

of the Wien filter fields. In case of an EDM in an ideal ring the maximum positive or negative buildup can be observed at $\phi_{\mathrm{WF}} = 0°$ or $\phi_{\mathrm{WF}} = 180°$, respectively. Assuming randomly Gaussian distributed misalignments of the COSY lattice quadrupoles the amplitude and phase dependence is spoiled and differs for various randomization seeds. The good agreement between the analytical estimation and the tracking results can be considered as a further verification of the map based method for radiofrequency fields. This allows for a systematic study of the impact of misalignments for the proposed EDM searches. Additional radial fields are a main contribution to tilts of the spin closed orbit of the static ring. In the presented scenario these fields occur in the vertically shifted quadrupoles. Besides the spin motion, also the beam motion is affected inside these fields. The additional deflections lead to a different closed orbit solution. Therefore, the vertical orbit displacements with respect to the quadrupole centers are an appropriate observable. Different magnitudes of the standard deviation of the Gaussian distributed quadrupole shifts between 1 µm and 1 mm have been simulated. For each of these misalignment sets a tracking simulation has been performed using different

EDM magnitudes. The Wien filter fields' phase has been locked to the situation of maximum buildup. This results in the shown buildup for different RMS values of the vertical orbit displacements at the quadrupoles in Fig. 5. As long as the EDM contribution to the buildup is significantly larger than the buildup introduced by misalignments both effects are distinguishable. For a randomized error standard deviation of 0.1 mm, the RMS value of the displacements is around 1 mm. For that value, the contribution to buildup from misalignments is similar to an EDM contribution for $\eta = 10^{-4}$. This corresponds to $d \approx 5 \cdot 10^{-19}\,\mathrm{e} \cdot \mathrm{cm}$.

SUMMARY

Transfer maps for time-varying fields have been implemented into an COSY INFINITY extension and could be successfully benchmarked. As part of the benchmarking process rf solenoid induced spin resonances have been studied. The dependence of the vertical polarization oscillation damping on the rf solenoid frequency has been demonstrated in measurements, calculations and tracking simulations. Furthermore analytical predictions for the EDM related buildup for particles on the closed orbit could be verified by tracking simulations. The impact of randomly Gaussian distributed quadrupole misalignments has been studied and reveals a similar polarization buildup as for an EDM of $d \approx 5 \cdot 10^{-19}\,\mathrm{e} \cdot \mathrm{cm}$ for a misalignment standard deviation of 0.1 mm. The prospects of suppressing the influence of systematic effects by a precise orbit diagnosis and control system are part of ongoing studies.

ACKNOWLEDGMENT

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