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Spin Tune Response to Vertical Orbit Correction at COSY

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Searches of electric dipole moments (EDM) of charged particles in pure magnetic rings, such as COSY, or electrostatic and hybrid magnetic-electric storage rings, planned in the future, require new methods to disentangle the EDM signal from the large background produced by magnetic dipole moments. In these experiments, the sources of systematic background are in-plane magnetic fields. It is important to distinguish the origins of the in-plane magnetic fields, which could be produced intentionally by vertical orbit correction to keep the beam on a closed path, or unintentionally due to the alignment errors of the magnets. We propose to use the method of spin tune mapping to determine the relative importance of those two origins. At the first stage, the model of COSY should be verified for the spin tune shifts when vertical three-steerer closed-orbit bumps are applied. At the second stage, the spin tune responce to vertical orbit correction in the arcs will testify its contribution to the systematic background.

KEYWORDS: spin tune, electric dipole moment, bump, orbit correction

1. Introduction

The electric dipole moment (EDM) signal constitutes a rotation of the spin in the electric field. In an all magnetic ring (COSY), it is the motional electric field $\propto [\vec{\beta} \times \vec{B}]$ along the radial x-axis around which the EDM precesses. As such, an EDM contributes also to a constant tilt of the stable spin axis

$$\vec{c} = \vec{e}_y + \xi_{\text{edm}} \vec{e}_x \tag{1}$$

On the other hand, nonuniform in-plane magnetic fields tilt the invariant spin axis towards x or z (see Fig. 1),

$$\vec{c} = c_y \vec{e}_y + \left(\xi_{\text{edm}} + c_x^{\text{mdm}} \right) \vec{e}_x + c_z^{\text{mdm}} \vec{e}_z. \tag{2}$$

While $c_y \simeq 1$, the projections $c_{x,z}$ depend on the specific location along the beam path s, chosen to define the one-turn spin transfer matrix. In-plane magnetic fields have two origins: one is the radial focusing fields of the quadrupoles and vertical steerers to control the beam on a closed orbit. Another one is imperfection fields produced by the uncontrolled alignment errors of the magnets. The spin rotations in the in-plane fields are non-commuting with the spin rotations around the vertical field of the dipoles. This leads to complex dependence of $\vec{c}$ on s. However, unlike $c_{x,z}^{\text{mdm}}$, the EDM contribution to $\vec{c}$ is *invariant* along the orbit. It gives possibility to disentangle the EDM and Magnetic Dipole Moment (MDM) effects if non-invariant part of $\vec{c}$ can be described.

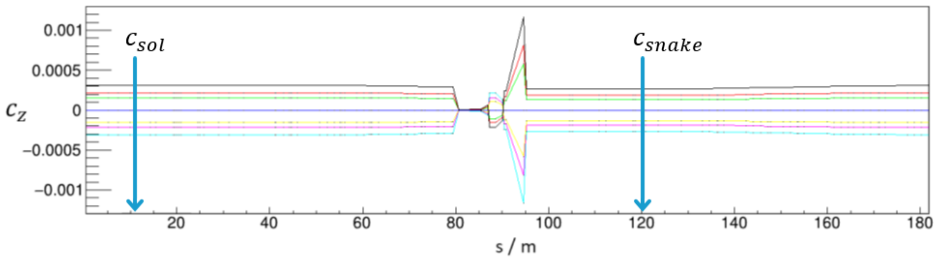

Fig. 1. Dependence of the in-plane component c_z of the invariant spin axis $\vec{c}$ along the closed orbit path s. Locations of two solenoids are marked by vertical arrows, and the values of c_z at those places are designated as c_{sol} and c_{snake}. Following bump amplitudes were used during the measurement: −4 mm (black), −3 mm (pink) to 3 mm (red), 4 mm (cyan)

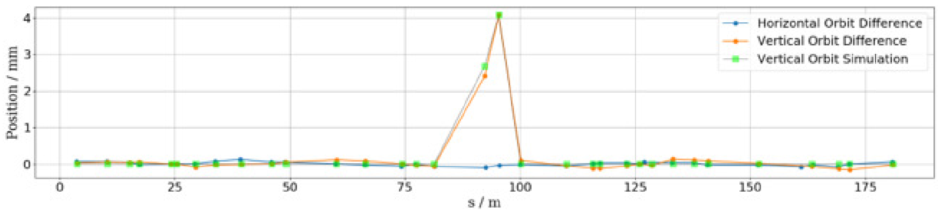

Fig. 2. Modelled (green) ideal vertical orbit and measured (orange-vertical, blue-horizontal) orbit difference between 85 (no bump) and 115 (bump applied) seconds in the beam cycle. The proportionality coefficients for steerers to create closed bump were determined from the simulated and measured Orbit Response Matrices correspondingly.

2. Selected results from JEDI experiment with vertical steerer bumps

In the JEDI experiment "Optimization of the alignment of magnetic elements using the spin tune response to three-steerer bumps" in fall 2020, we tested a demerit of spin rotations, a "commutation failure", by creating a controlled closed orbit distortion over 1/8 part of the ring circumference - a vertical closed orbit bump. The current in steerers MSV18, MSV20 and MSV22, which were used to create the bump, was adjusted for a special period of time during the beam storage cycles. The measured orbit difference between bump ON/OFF states is shown on Fig. 2.

An ideal model of COSY ring gives the prediction of $\vec{c}(s)$ (Fig. 1) for all of the bump amplitudes (for example, orbit simulation shown on Fig. 2). To track the closed orbit particle, beam and spin tracking package COSY-Infinity was used [1]. In order to determine the dependence of projection c_z on the bump amplitude in the experiment, we used a special method called "spin tune mapping" [2]. This method is based on the outstanding ability to determine the spin tune with a relative error of 1×10^{-10} during a 100 s long beam cycle at COSY from the time dependence of horizontal polarization [3]. For the same period of time in the cycles when the bump appears, two static solenoids, one in the target telescope, and one in the cooler telescope, were switched on. The spin tune was measured on the grid of solenoid currents $I_{1,2}$ applied at the fixed amplitude of the bump.

Parabolic dependence of the spin tune shifts $\Delta\nu_s$, which are calculated as a change of spin tune relative to the baseline spin tune value ν_s, given at the moment of time in cycle when the solenoid current and the bump amplitude were zero, fits non-lattice model where c_z (at $s = 16.27$ m $c_z = c_{\text{sol}}$ for the 2 MeV e-cooler compensation solenoid in target telescope and at $s = 126.13$ m $c_z = c_{\text{snake}}$ for superconducting snake solenoid at cooler telescope) and solenoid's current-to-spin-kick calibration

$k_{1,2}$ are free parameters:

$$-\pi\Delta\nu_s = (\cos a \cos b - 1)\cot \pi\nu_s - c_{\text{sol}} \sin a \cos b - c_{\text{snake}} \cos a \sin b - \frac{\sin a \sin b}{\sin \pi\nu_s}\,, \tag{3}$$

where

$$a = \frac{k_1 I_1}{2} \quad \text{and} \quad b = \frac{k_2 I_2}{2}\,. \tag{4}$$

As a result of the spin tune mapping (see example on Fig. 3), the values of c_z are determined with angular precision $\sigma_{c_{\text{sol}}} = 6.9\,\mu$rad at the 2 MeV e-cooler solenoid and $\sigma_{c_{\text{snake}}} = 3.6\,\mu$rad at superconducting snake. The relative error on the spin tune shift $\Delta\nu_s$ is $\sigma_{\Delta\nu_s} = 3.7 \times 10^{-9}$.

When two static solenoids located at COSY telescopes are used, position dependence of $\vec{c}(s)$ is only partly uncovered. Nevertheless, fit results for spin tune maps at all of the measured bump amplitudes are in good agreement (up to 8% difference) with the model prediction for dependence of c_z projections at solenoids from the central steerer setting (see Fig. 4). The values of central steerer (MSV20) that correspond to the same amplitude of the bump in the model and measurement were chosen as a reference ones. The settings for MSV18 and MSV22 were selected accordingly to fulfill the condition of closed orbit bump, which is derived from the simulated (in case of model) and measured (in experiment) orbit response matrix. It means as a matter of fact, that *we created local orbit distortion by horizontal magnetic fields in the ring and described the resulting beam and spin dynamics*. Note that an offset between measured (obtained from spin tune map fits) and simulated data points at Fig. 4 is non-vanishing due to the presence of alignment errors in the ring, which contribute to the tilt of invariant spin axis towards z-axis.

2.1 New proposal

The new experiment proposal aims at probing the local properties of the focusing fields at COSY. At first stage, spin tune maps with all available vertical three-steerer bumps in the arcs should be measured and compared to the model (12 bump configurations in total). In a second stage of experiment, spin-tune mapping scheme with a global vertical orbit correction will be scrutinized. The current in all vertical steerers will be scaled down in consequtive experiment setups. For each setup, all vertical 3-steerer bumps will be used to determine $\vec{c}(s)$. One important feature is that the currents for vertical steerers at straight sections of COSY will be calculated such that the orbit in the solenoids, polarimiter and RF cavity would remain the same for all setups. This allows us to witness the impact of the applied vertical orbit correction at COSY on the observed tilt of the invariant spin axis (the measured offset of c_{sol} and c_{snake} at zero bump amplitude in Fig. 4 for the z-projection of $\vec{c}$). Finally, the studies should be repeated for protons, once a sufficiently long spin-coherence time is achieved in the JEDI experiment ”Measurement and Optimization of the Spin Coherence Time for Protons in COSY” (based on [4] and [5]).

3. Conclusion and Outlook

The quantitative understanding of the local sources of the imperfection fields and their active compensation is indispensable for disentangling the EDM effect from the EDM-like background from interactions of the vastly larger magnetic dipole moment with the in-plane magnetic fields.

Developed method is applicable in the future storage rings as a tool for diagnostics of beam and spin dynamics when approaching frozen spin condition. At prototype EDM ring, it can be applied at 30 MeV counter-circulating protons, to verify the achievements of the beam and spin-dynamic studies at pure magnetic rings with non-frozen spin. It is an important connecting step to test the model predictions for pure electrostatic lattice, preceding the measurements at strictly frozen spin condition.

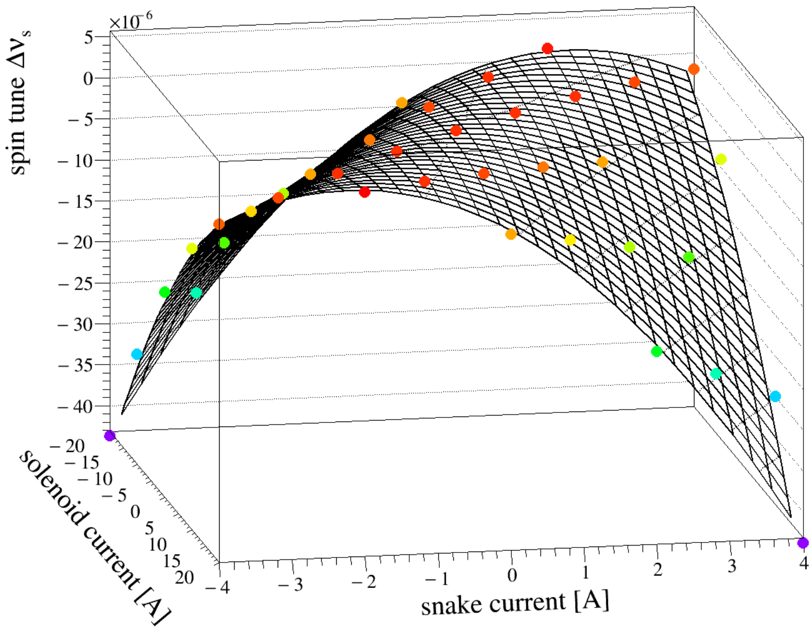

Fig. 3. One of the spin tune maps measured at fixed bump amplitude 3 mm. Surface is a fit to data points (colored circles) by Eq. (3).

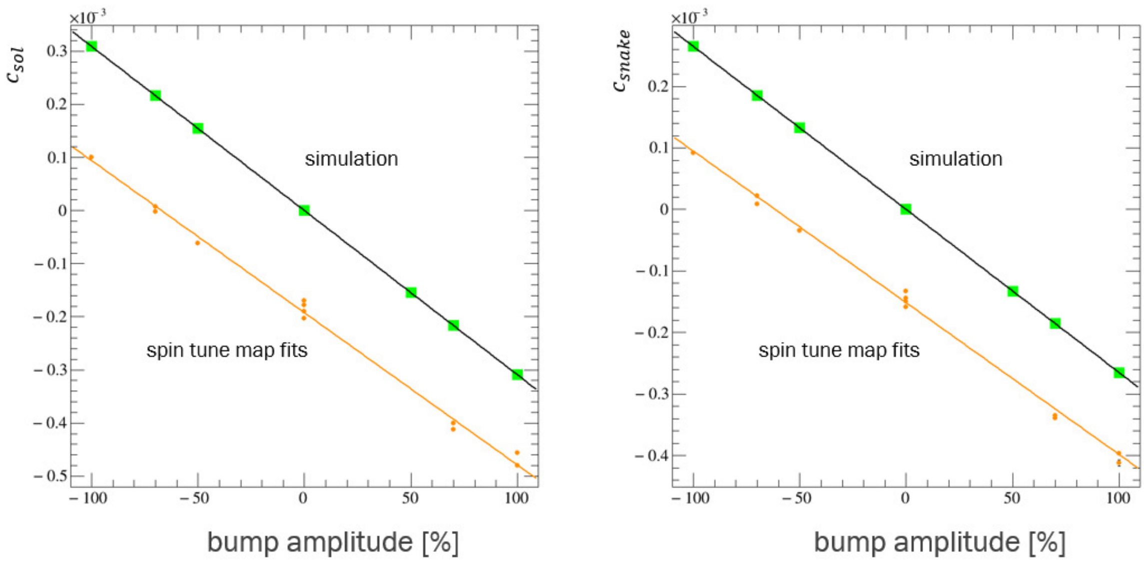

Fig. 4. Dependence of the fit parameters c_{sol} and c_{snake} on the bump amplitude and comparison to simulation results. Value 100% corresponds to the bump amplitude of −4 mm.

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