SPIN TUNE RESPONSE TO VERTICAL ORBIT CORRECTION AT COSY

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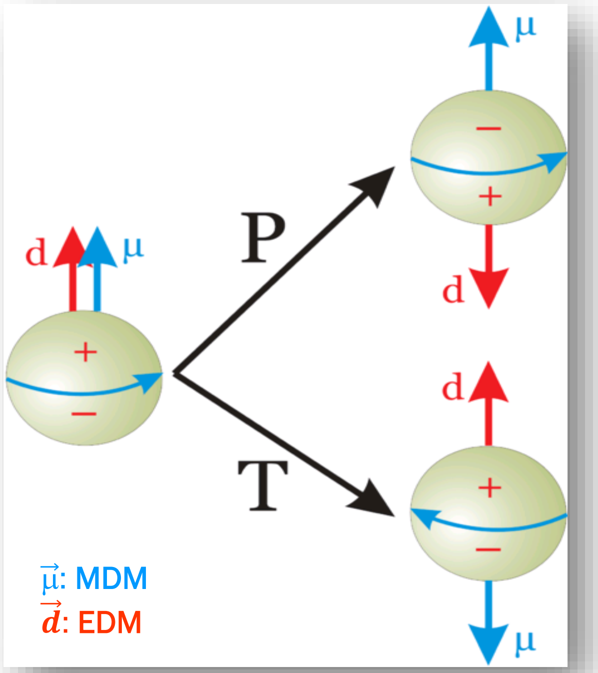
WHY TO SEARCH FOR THE ELECTRIC DIPOLE MOMENT

- Matter-antimatter asymmetry in the universe is observed, $\frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$, while Standard Cosmological Model predicts only $\sim 10^{-18}$ with allowance for (C)harge(P)arity-violation, -> confirmations of CP violation are needed to add new features in the model (baryogenesis, A. Sakharov, 1967)

- EDM: $\vec{d} = \sum \vec{r}_i e_i \xrightarrow[\text{subatomic}]{} d \cdot \vec{S}/S$

- which means(P)arity- and (T)ime-reversal symmetries broken

- It leads to CP-violation if CPT-symmetry is conserved



SEARCHING CHARGED PARTICLE’S EDM IN STORAGE RINGS

- The particles’ spins $\vec{S}$ would precess, according to Thomas-BMT eq.:

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}(t) = -\frac{q}{m}\left(\underbrace{G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G\right)\vec{\beta} \times \vec{E}}_{\text{MDM}} + \underbrace{\eta(\vec{E} + \vec{\beta} \times \vec{B})}_{\text{EDM}} \right) \times \vec{S}(t)$$

- Symmetry-conserving Magnetic Dipole Moment (MDM) term
- CP-violating Electric Dipole Moment (EDM) term $\sim\eta$
- Velocity $\vec{\beta} = \frac{\vec{v}}{c}$, and Lorentz factor γ
- Inherent feature: anomalous magnetic moment is G is expected $\sim 10^{10}$ larger than η for EDM of deuterons $10^{-24} e \cdot cm$
- How to suppress spin rotation due to MDM?

DIRECT MEASUREMENT OF PROTON EDM

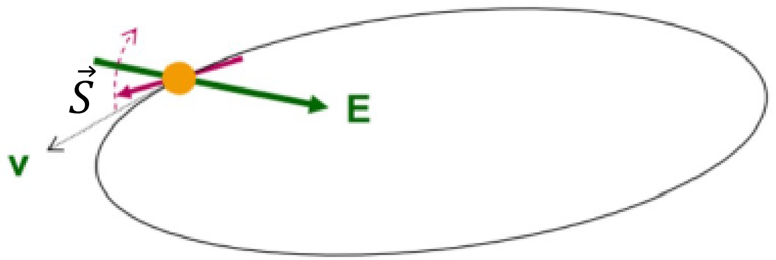
- Such special condition when momentum stays aligned with polarization, is called “frozen spin”

- At T=45 MeV – at Prototype EDM ring (see https://doi.org/10.23731/CYRM-2021-003),
  when the beam is guided to circular path with combined horizontal E_x and vertical B_y fields such that

$$G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G\right)\vec{\beta} \times \vec{E} = 0$$

- At T=232 MeV – pure electrostatic ring, only E_x,

$$\left(\frac{1}{\gamma^2 - 1} - G\right)\vec{\beta} \times \vec{E} = 0$$

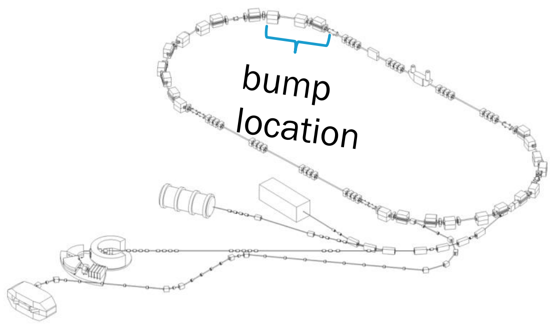


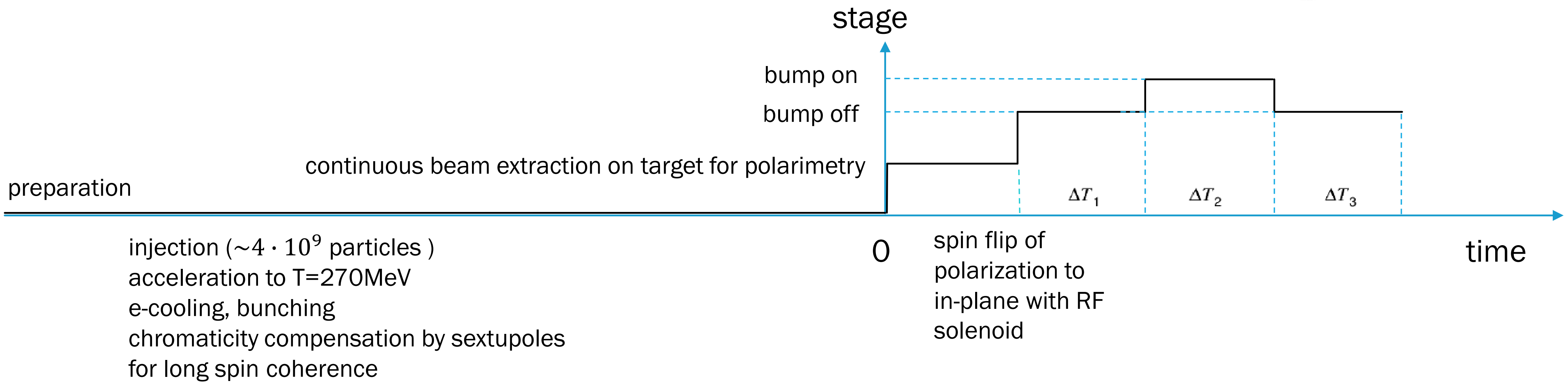
- The out-of-plane build-up of vertical polarization $S_y \sim \eta \cdot t$

- To cancel out systematics: run the beam in opposite directions, CW and CCW, on **equal orbits**

THE EXPERIMENT AT COSY

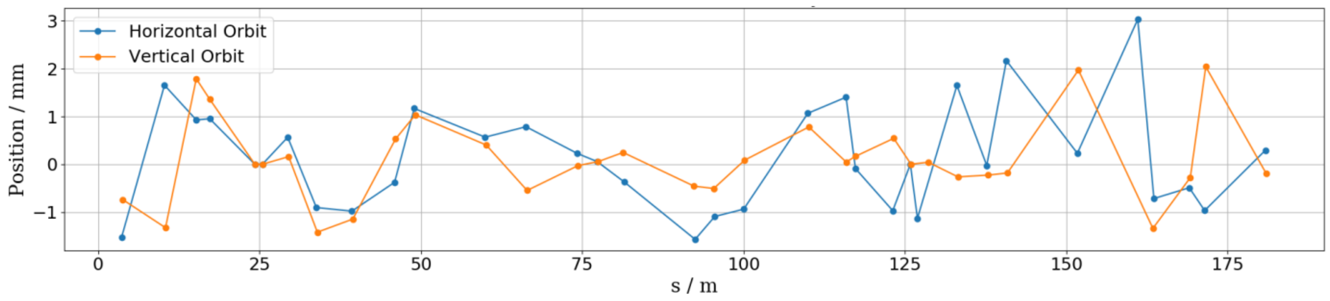
- COSY is pure magnetic ring: spin is not frozen
- Imitate inequality of CW and CCW beam orbits by vertical orbit excursion - an “orbit bump”
- Bump steerers ON at ΔT_2 and OFF at ΔT_1, ΔT_3
- Determine relative orbit shift between ΔT_2 and $\Delta T_{1,3}$



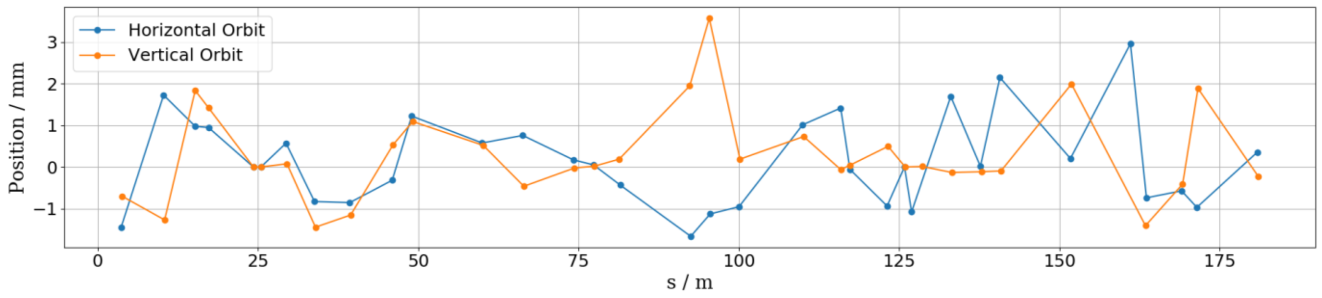


ORBITS MEASURED WITH BUMP ON AND OFF

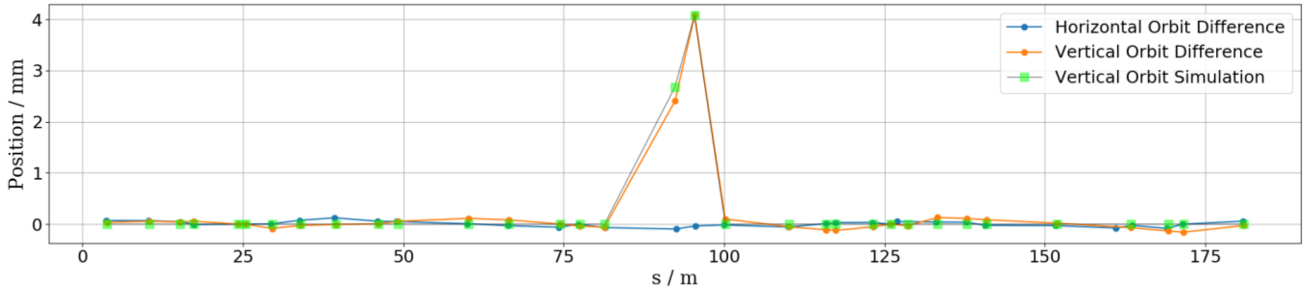
- Orbit at ΔT_1 and ΔT_3 :



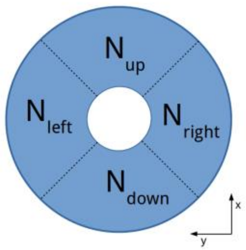
- Bump applied at ΔT_2 :



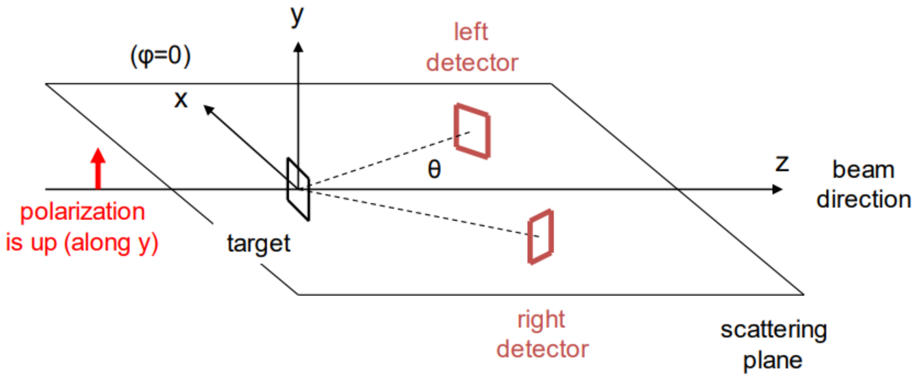
- Observed orbit difference is compared to simulation of the bump with beam and spin tracker “COSY-Infinity”:



MEASUREMENT OF BEAM POLARIZATION



2π detector - "beam" view



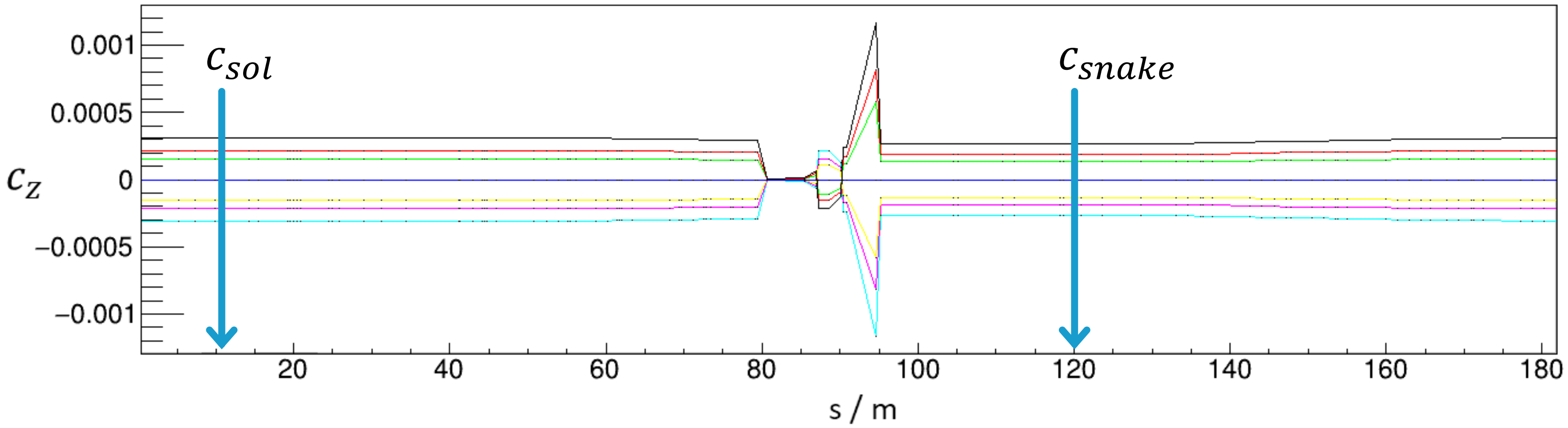
Right/Left asymmetry ∝ vertical polarization P_y → **EDM signal appears here**

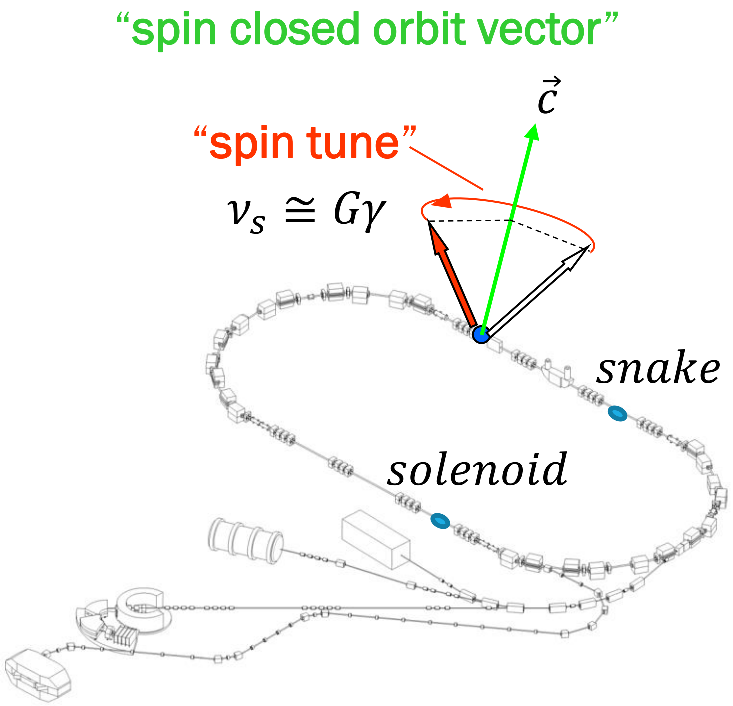
Up/Down asymmetry ∝ horizontal polarization P_x → **Determine spin tune**

- Scattering from Carbon target
- Time stamping system assigns each event a turn number; count rate ~5 kHz; revolution freq. 750 kHz; 1 hit per 25 turns
- By Fourier Transform of Up/Down detector events, the number of spin rotations per turn - spin tune ν_s - is determined with relative precision $\delta_{\nu_s} = 10^{-10}$ in 100s of beam cycle

SPIN CLOSED ORBIT

- Predict $c_z(s)$ for every amplitude of the bump from -4 mm (black) to +4 mm (cyan):





- Non-commutation of spin rotations in vertical field of bend dipoles and horizontal field of steerers and quadrupoles along the span of the bump
- Example at solenoids: $c_z = c_{sol}$ and $c_z = c_{snake}$, while $c_{sol} \neq c_{snake}$
- Measure the change of spin tune $\Delta\nu_s$ relative to bump and solenoid currents to find such c_{snake}, c_{sol} in the experiment

THE METHOD OF SPIN TUNE MAPS WITH SOLENOIDS*

- The two solenoids were powered simultaneously with magnets of the steerer bump at ΔT_2 in the beam cycle

- The spin tune shifts $\Delta \nu_s$ with respect to solenoid currents I_1, I_2, relative to base spin tune ν_s at $\Delta T_{1,3}$ fits to:

$$-\pi \Delta \nu_s = \cot \pi \nu_s \left(\cos \frac{k_1 I_1}{2} \cos \frac{k_2 I_2}{2} - 1\right) - (c_{sol}) \sin \frac{k_1 I_1}{2} \cos \frac{k_2 I_2}{2}$$

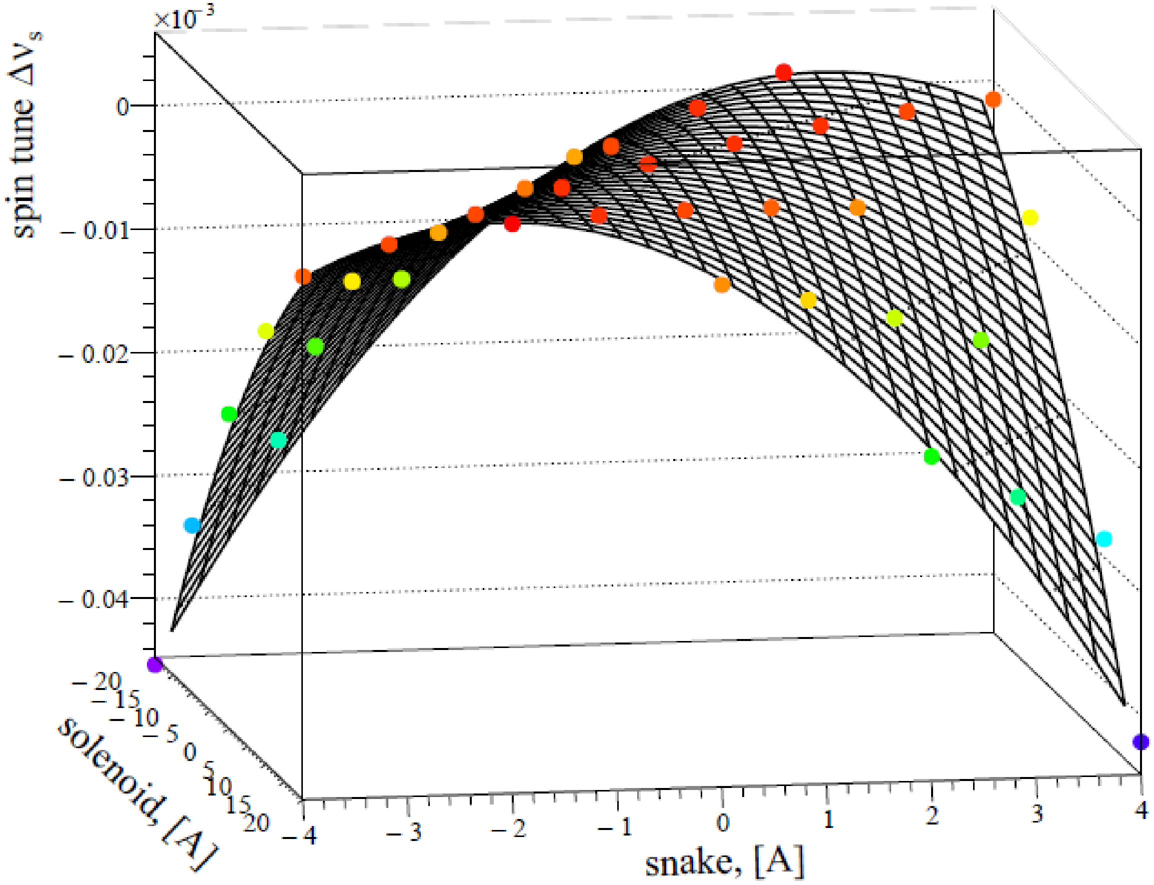
$$- \frac{1}{\sin \pi \nu_s} \sin \frac{k_1 I_1}{2} \sin \frac{k_2 I_2}{2} - (c_{snake}) \sin \frac{k_2 I_2}{2} \cos \frac{k_1 I_1}{2}$$

- Measure $\Delta \nu_s$ on the grid of settings I_1, I_2 and constant amplitude of the bump

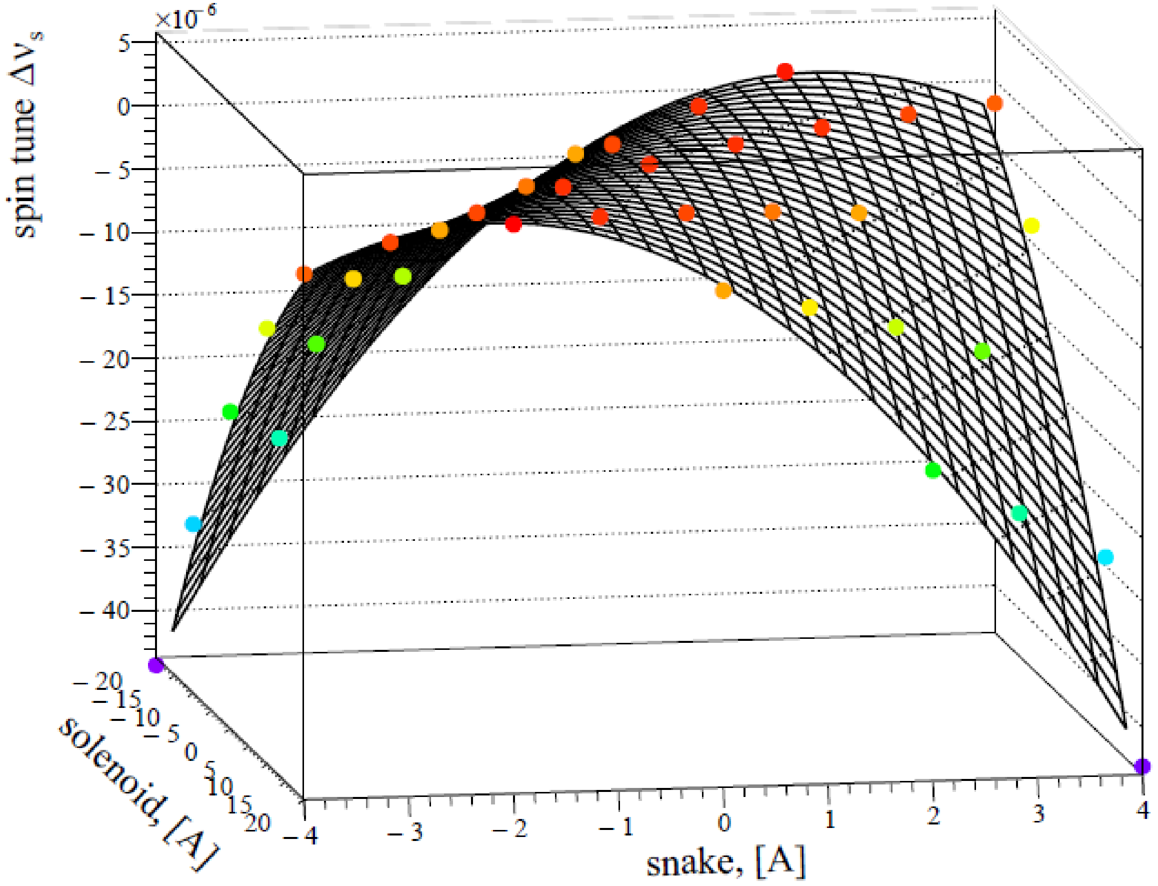
*Phys. Rev. Accel. Beams 20, 072801 (2017)

SPIN TUNE MAPS

- Position of saddle point defines parameters c_{snake} and c_{sol} - is influenced by the bump



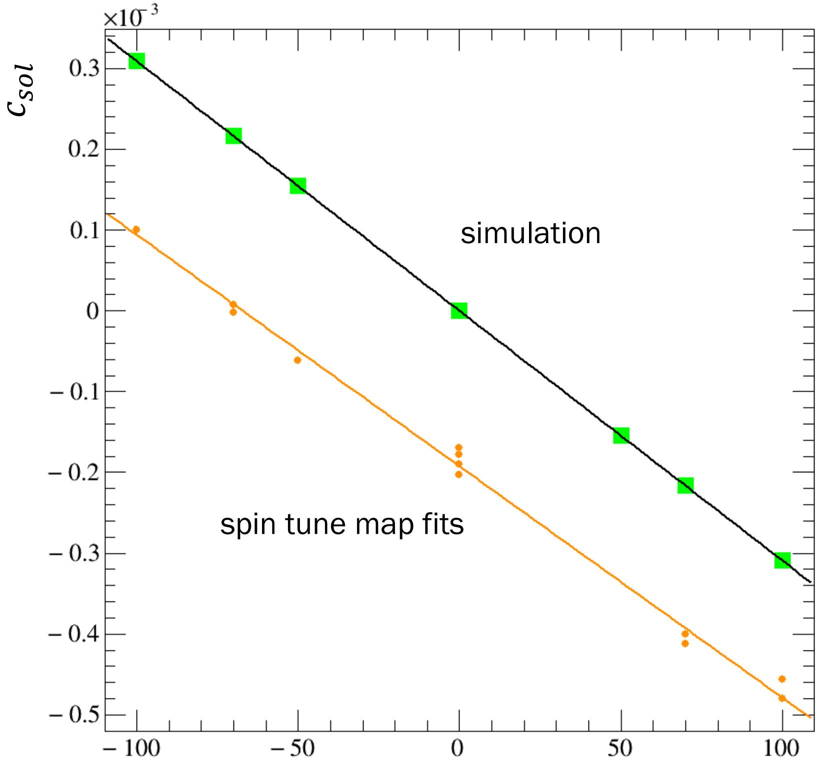
bump amplitude -3 mm



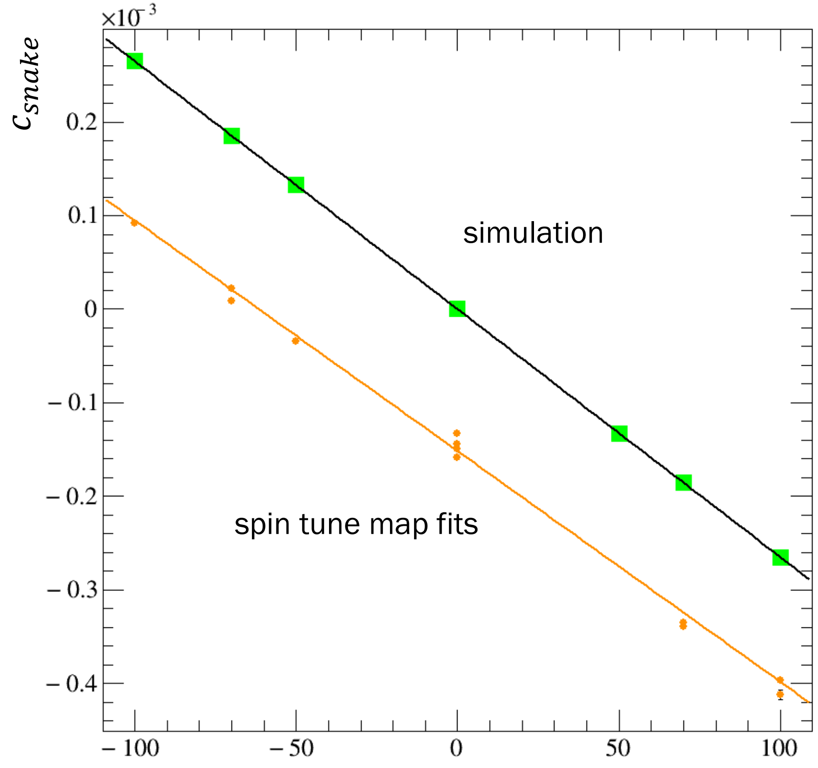
bump amplitude +4 mm

AGREEMENT WITH MODEL

- Bump influence on c_{sol} and c_{snake}, determined from spin tune maps and from simulation in COSY-Infinity:



bump amplitude [%]



bump amplitude [%]

$\sigma_c = 0.3\ \mu rad$, -> potential sensitivity $\sigma_d = 10^{-21} e \cdot cm$ for one 100-seconds beam storage cycle

- Slopes differ by ~8%

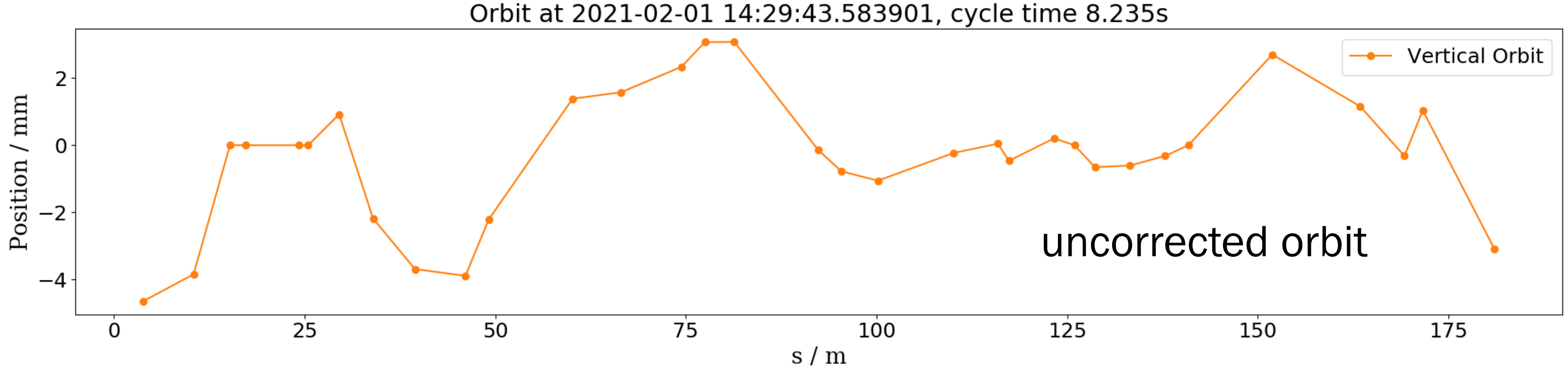
SUMMARY

- In the view of future experiments to search EDM at storage rings with CW/CCW beams, we made a “proof-of-principle”: prediction of systematic contribution of MDM spin rotations into beam polarization, produced by inequality of two beam orbits, is confirmed experimentally

- Combining the method with direct measurement of EDM using the RF Wien filter (see group report HK 73.1 by V.Shmakova on Thursday, 16:00 HK-H9) leads to potential sensitivity to EDM of deuterons at COSY $\sigma_d = 10^{-21} e \cdot cm$ for 100-s of beam storage cycle

OUTLOOK: EXPOSING THE EFFECT OF ALIGNMENT ERRORS

- Uncorrected vertical orbit exposes the effect of the magnet alignment errors:



- Apply orbit correction and scale it down to zero, while keeping it fixed at snake for proper spin tune mapping: