SPIN TUNE RESPONSE TO VERTICAL ORBIT CORRECTION AT COSY

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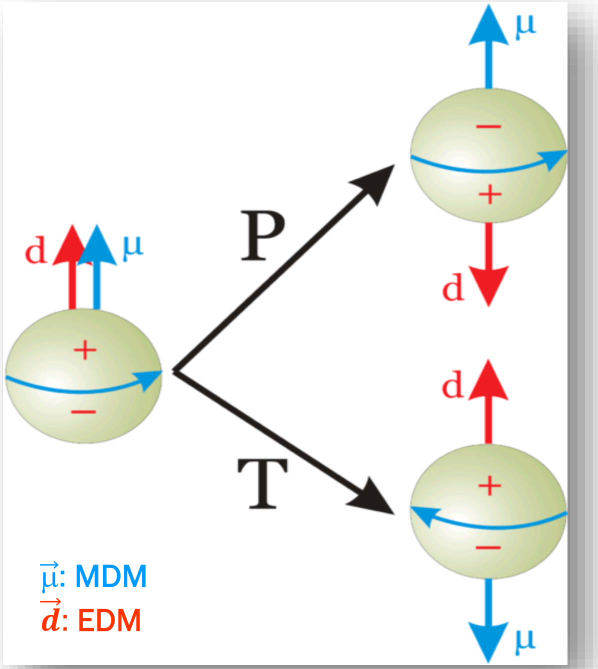
WHY TO SEARCH FOR THE EDM

- 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



DIRECT MEASUREMENT OF EDM OF CHARGED PARTICLES AT STORAGE RINGS

- Formulation of the problem: set the limit on the EDM of charged particles, such as protons and deuterons

- Solution in theory / practice:

1. Confine the particles as a beam at fixed energy – in a “storage ring” / construction and operation of an EDM-dedicated storage ring
2. For sufficiently long time, observe CP-violating motion of particles’ spins / coeherence of particles’ spins preserved vs time in such ring
3. Set the confident limit at which there are no CP-violating EDM-induced spin rotations observed / defining the systematic limitations of the experiment ← topic of discussion

SPIN DYNAMICS

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

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

- 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 $10^{-24} e \cdot cm$
- What are special conditions, when direct measurement of EDM from time-dependance of beam polarization is possible?

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,

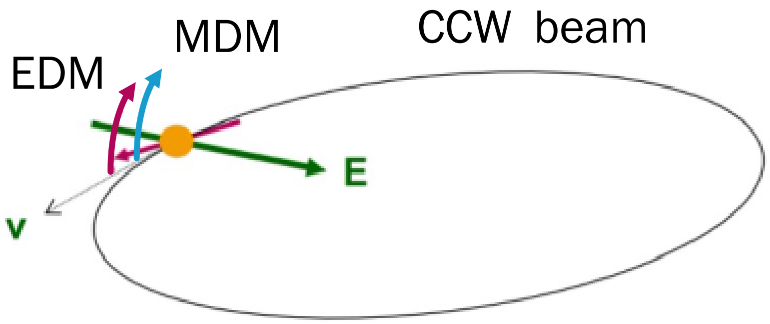
$$\left(\frac{1}{\gamma^2 - 1} - G\right) = 0$$

- In both cases, in the presence of EDM, the build-up of vertical polarization $S_y \sim \eta \cdot t$ should be observed

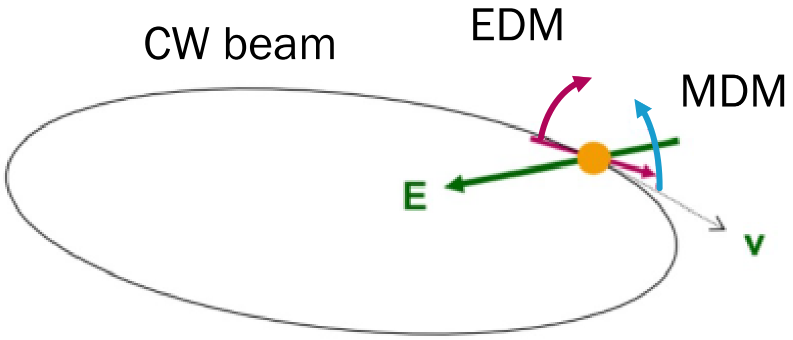
- MDM mimics EDM build-up in S_y in case of spurious E_y and B_x fields

COUNTER-CIRCULATING BEAMS

- In order to disentangle MDM and EDM contributions, run the beam in opposite directions:



P-, or T- symmetric:



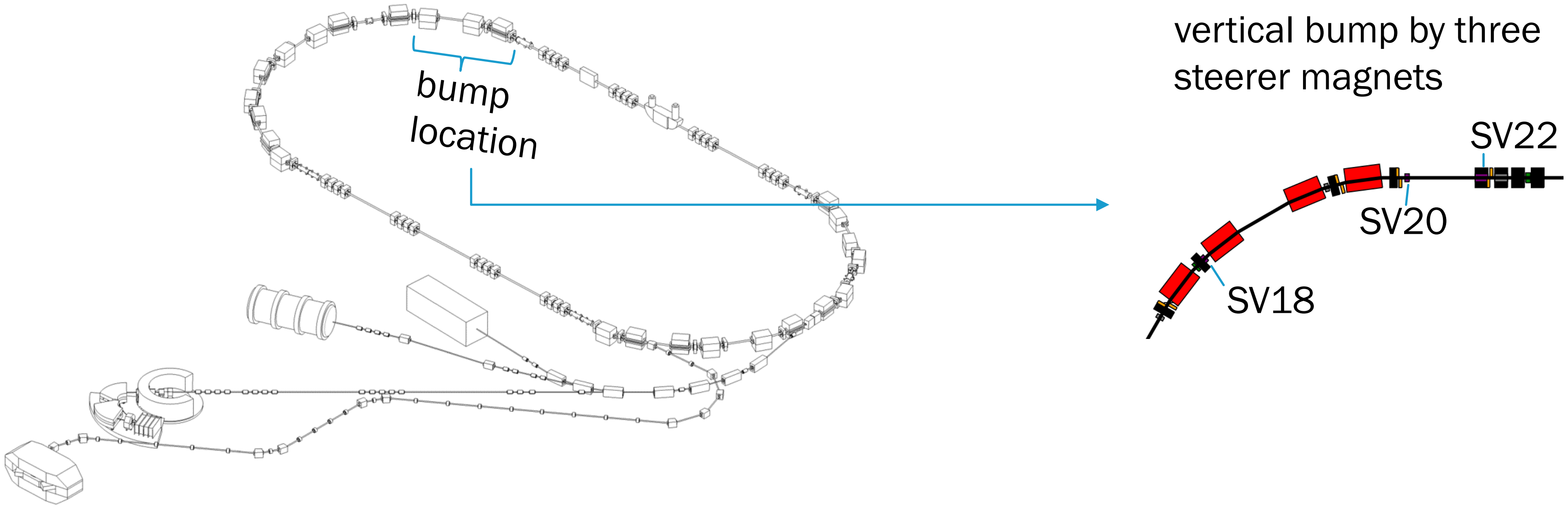
- CP-violating EDM would not change the direction of out-of-plane polarization build-up in CW and CCW runs, but
- <u>all the MDM–induced</u> spin rotations will have opposite sign
- P-, or T- symmetric experiment conditions implies that the orbits of CW and CCW beams <u>**should be the same**</u>

SYSTEMATIC LIMITATIONS IN THE SEARCHES OF EDM AT STORAGE RINGS

- The systematic limitation in the observation of the EDM signal comes from inequality of CW and CCW beam orbits, when:
- polarity of $\vec{B}$ -field is not exactly reversed between CW and CCW runs (especially in case of Prototype EDM ring)
- different energies of CW and CCW beams will cause different MDM contribution
- In order to set the EDM limit, one must take the systematic contribution of MDM under control

THE EXPERIMENT AT COSY

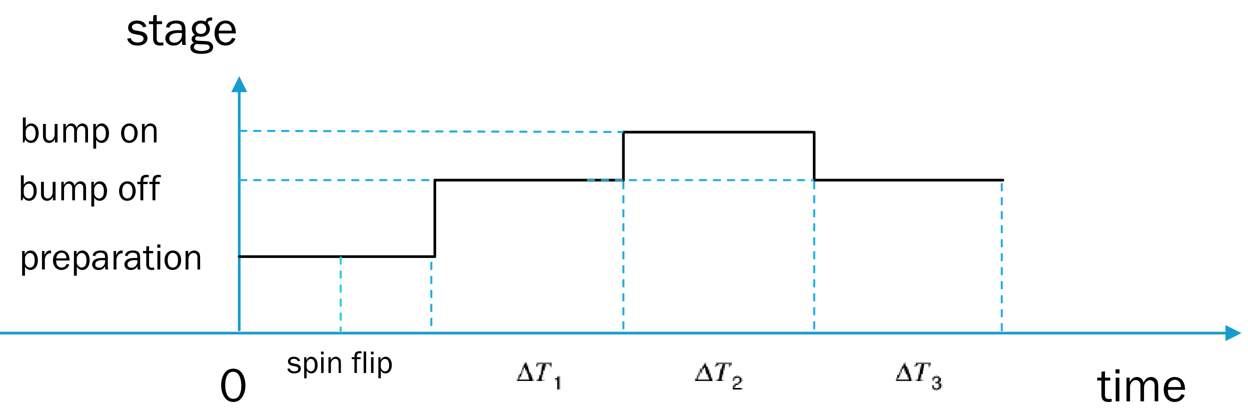
- COSY is pure magnetic ring (~183 m circumference), only CW beam available



- Recent experiment in September 2020 at COSY
- Imitation of inequality of CW and CCW beam orbits: by local orbit excursion - an “orbit bump”
- Measure the polarization for two orbits of the same beam, with and without bump, during one storage cycle

THE TIMELINE OF ONE STORAGE CYCLE

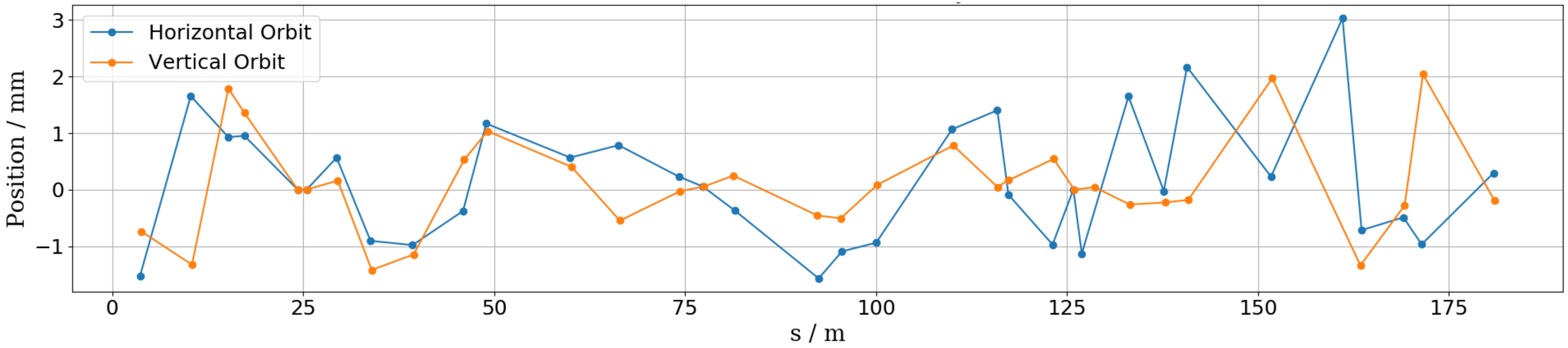
- Two experiment conditions: bump on and off, resulting in two orbit states
- Spin-flip of polarization in-plane, where it starts rapidly precessing, by resonant method with RF-solenoid spin flipper



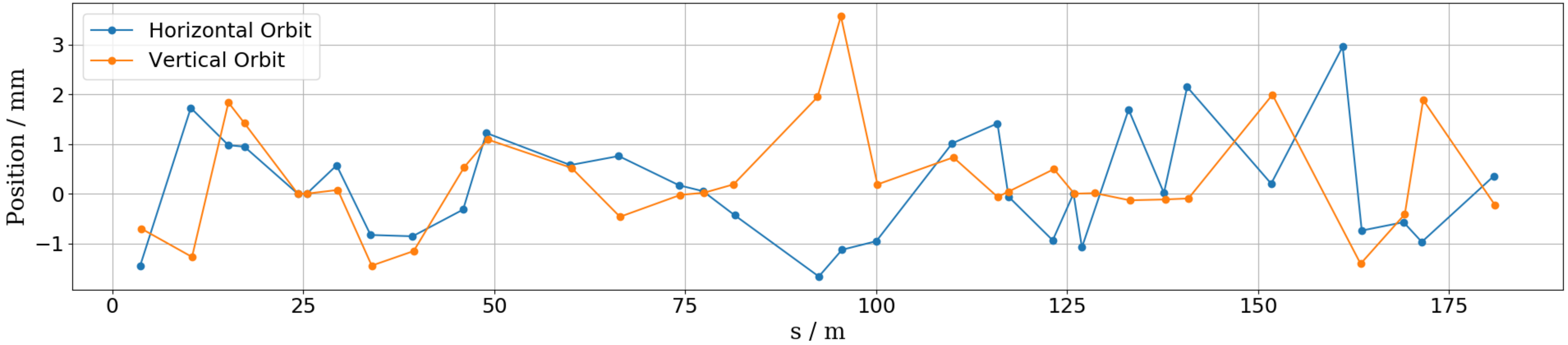
injection ($\sim 10^{10}$), acceleration to T=270MeV;
bunching, e-cooling, continuous extraction;
chromaticity compensation by sextupoles

TWO ORBITS OF THE SAME BEAM

- Orbit as measured without bump:

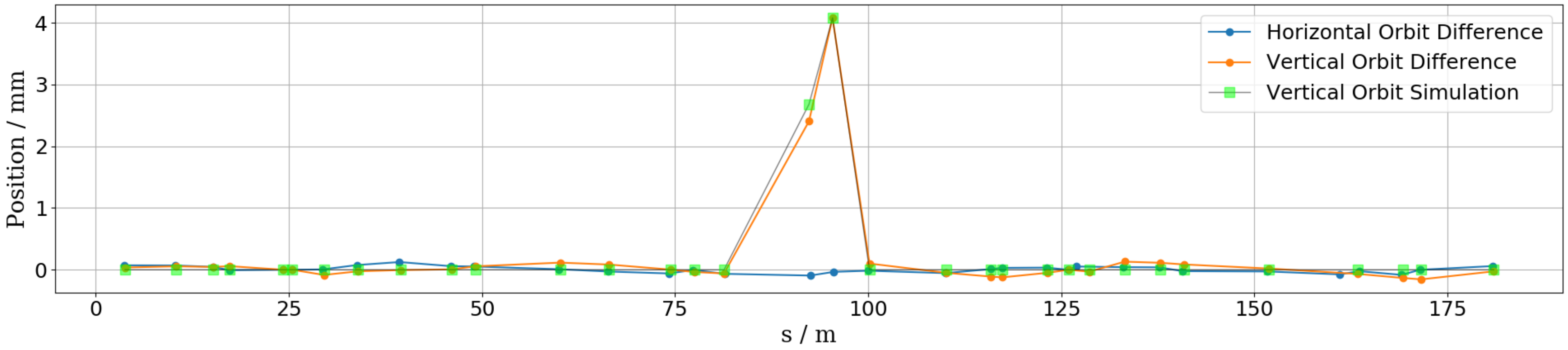


- Vertical bump applied 20 seconds later in the beam cycle:



RELATIVE DIFFERENCE OF TWO ORBITS

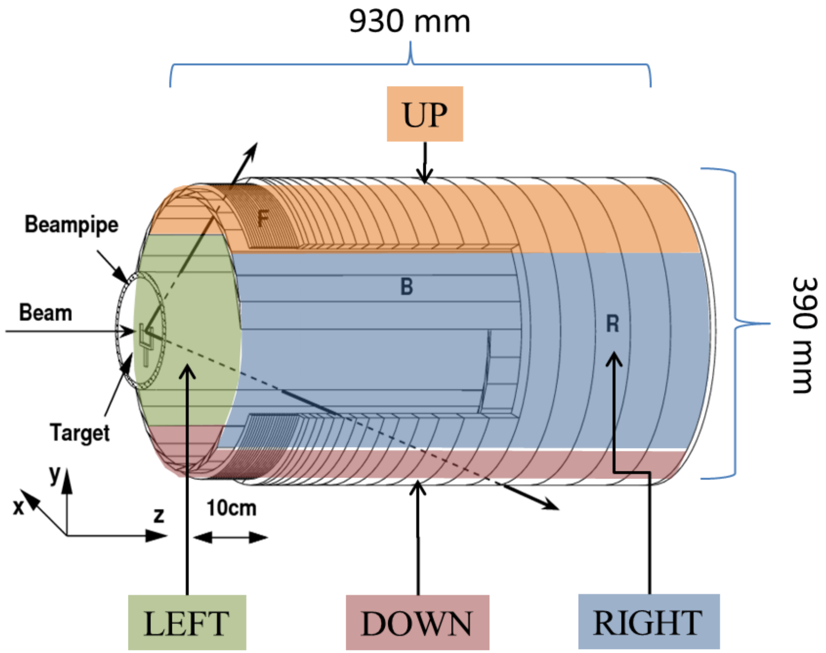
- Observed orbit difference shows sufficiently local orbit bump: vertical orbit shift outside of bump region RMS < 0.2 mm



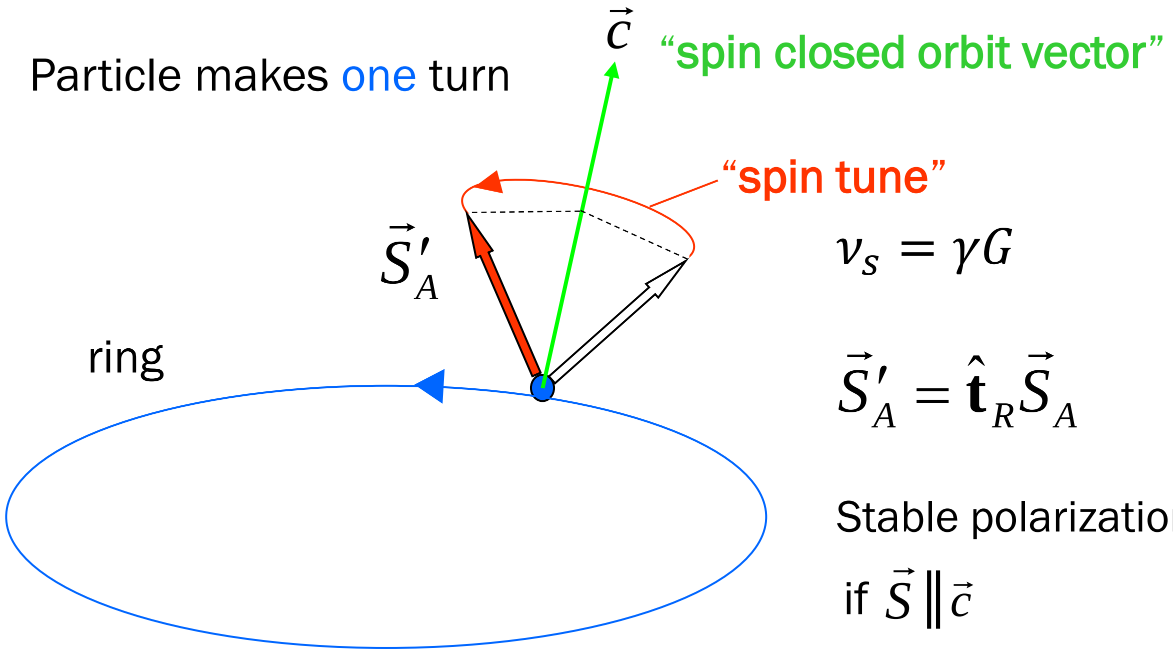
- Such vertical orbit bump was also reproduced in the simulation with beam and spin tracker “COSY-Infinity”
- Non-commutation of spin rotations in vertical field of bend dipoles and horizontal field of steerers and quadrupoles

MEASUREMENT OF BEAM POLARIZATION

- The white noise is applied by stripline unit, some particles will move to higher amplitudes in the oscillation trajectories,
- and eventually scatter on a carbon block target; depending on the spin, $\vec{S}$, they will hit different parts of the detector
- Time stamping system assigns each event a turn number; count rate ~5 kHz; revolution freq. 750 kHz; 1 hit per 25 turns



TIME DEPENDANCE OF BEAM POLARIZATION



$\nu_s = \gamma G$

$\vec{S}'_A = \hat{\mathbf{t}}_R \vec{S}_A$

Stable polarization

if $\vec{S} \parallel \vec{c}$

- The number of spin precessions per turn is called spin tune ν_s
- By Fourier Transform of detector events, the spin tune is determined with relative precision $\delta_{\nu_s} = 10^{-10}$ in 100s beam cycle

SPIN CLOSED ORBIT

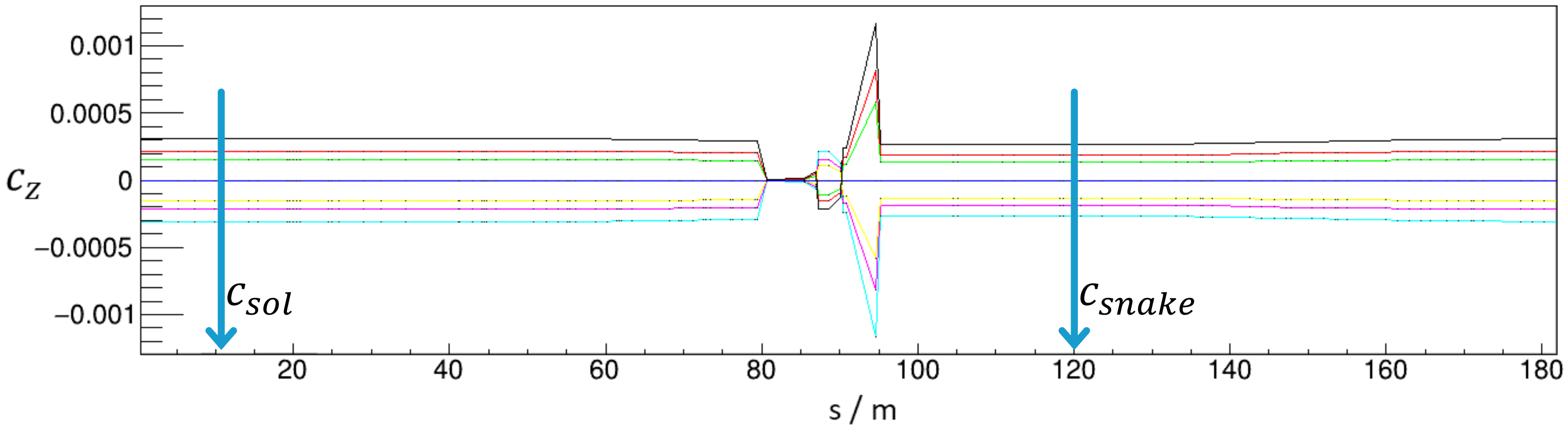
- Since $\hat{t}_R = \prod_{i=1}^{n} \hat{t}_i$, where $\hat{t}_i$ is a spin kick in the i-th magnet in the ring (out of total n elements), one could define $\vec{c}$ after every k-th magnet, and it will not be the same due to non-commutativity of spin kicks:

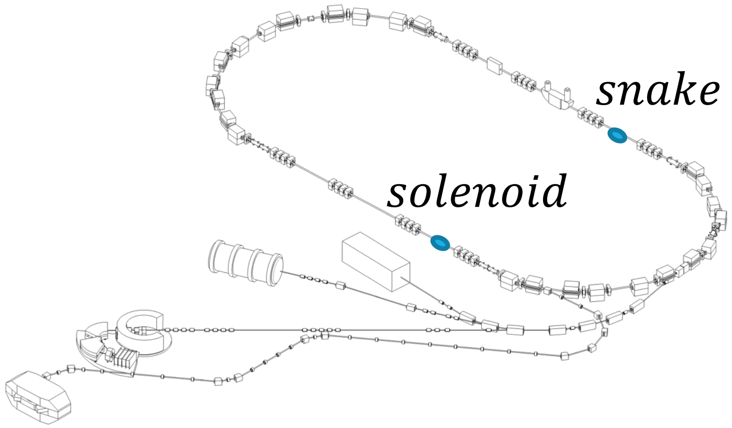
$$\prod_{i=1}^{n} \hat{t}_i = \prod_{i=1}^{k} \hat{t}_i \prod_{l=k+1}^{n-k} \hat{t}_l \neq \prod_{l=k+1}^{n-k} \hat{t}_l \prod_{i=1}^{k} \hat{t}_i$$

- Which means, spin closed orbit $\vec{c}$ after magnet n differs from that after magnet k
- This also is confirmed in simulation; horizontal projections of $\vec{c}$ depend on the s-position of viewpoint in the ring, which could be defined after each magnet

THE METHOD OF SPIN TUNE MAPS WITH SOLENOIDS

- Predict $c_z(s)$ for every amplitude of the bump from -4 mm (black) to +4 mm (cyan), in particular $c_z = c_{sol}$ and $c_z = c_{snake}$:





- Projection of $c_z(s)$ exhibits the contribution of non-commuting spin rotations by Magnetic Dipole Moment coming from the observed change in the beam orbit by the bump
- However, the change of spin tune, $\Delta\nu_s$, is small and should be amplified by using two static spin rotators – solenoids

SPIN TUNE MAPS*

- The two solenoids were powered simultaneously with magnets of the steerer bump

- The spin tune shifts $\Delta\nu_s$ with respect to solenoid currents I_1, I_2, relative to spin tune ν_s at $I_1 = I_2 = 0$ and bump off, fits to:

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

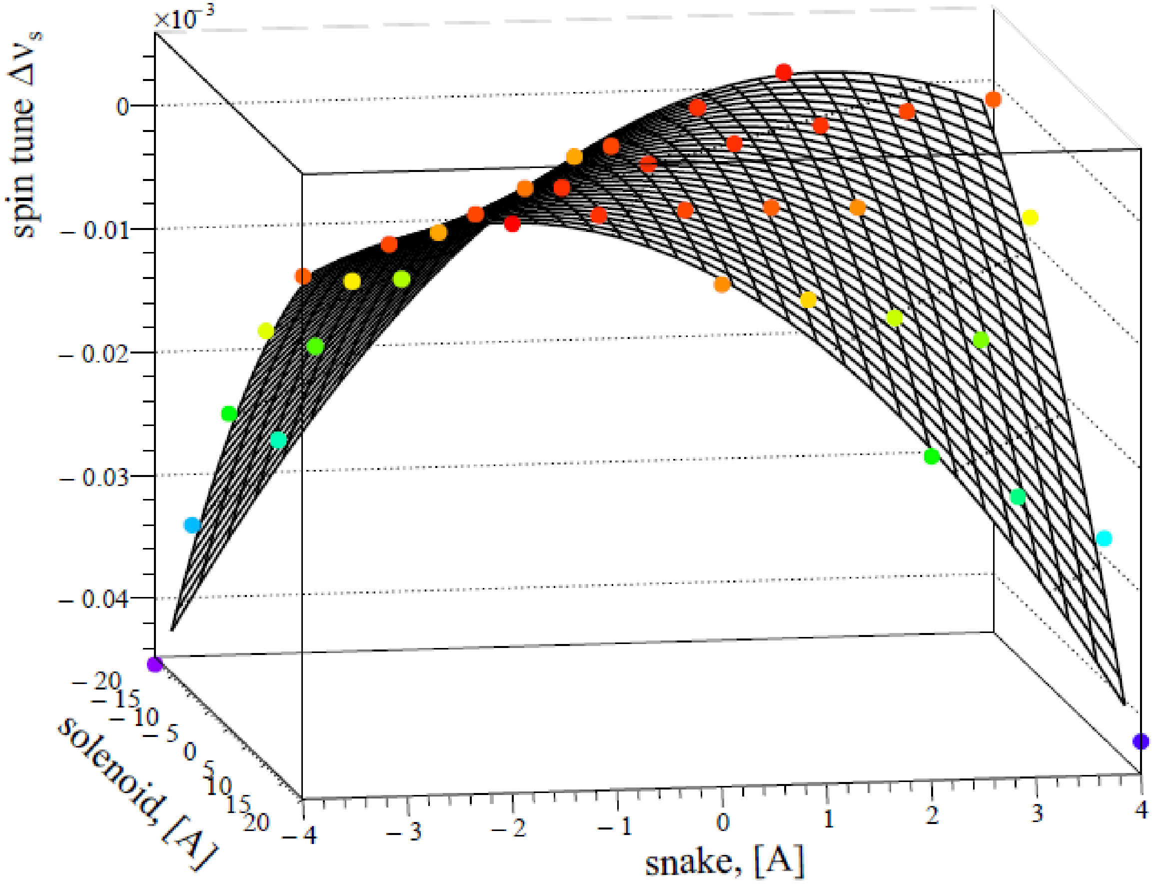
$$-\frac{1}{\sin\pi\nu_s}\sin\frac{k_1 I_1}{2}\sin\frac{k_2 I_2}{2} - (c_{snake})\sin\frac{k_2 I_2}{2}\cos\frac{k_1 I_1}{2}$$

- Measure $\Delta\nu_s$ in every beam storage cycle, at certain settings of I_1, I_2 and constant amplitude of the bump

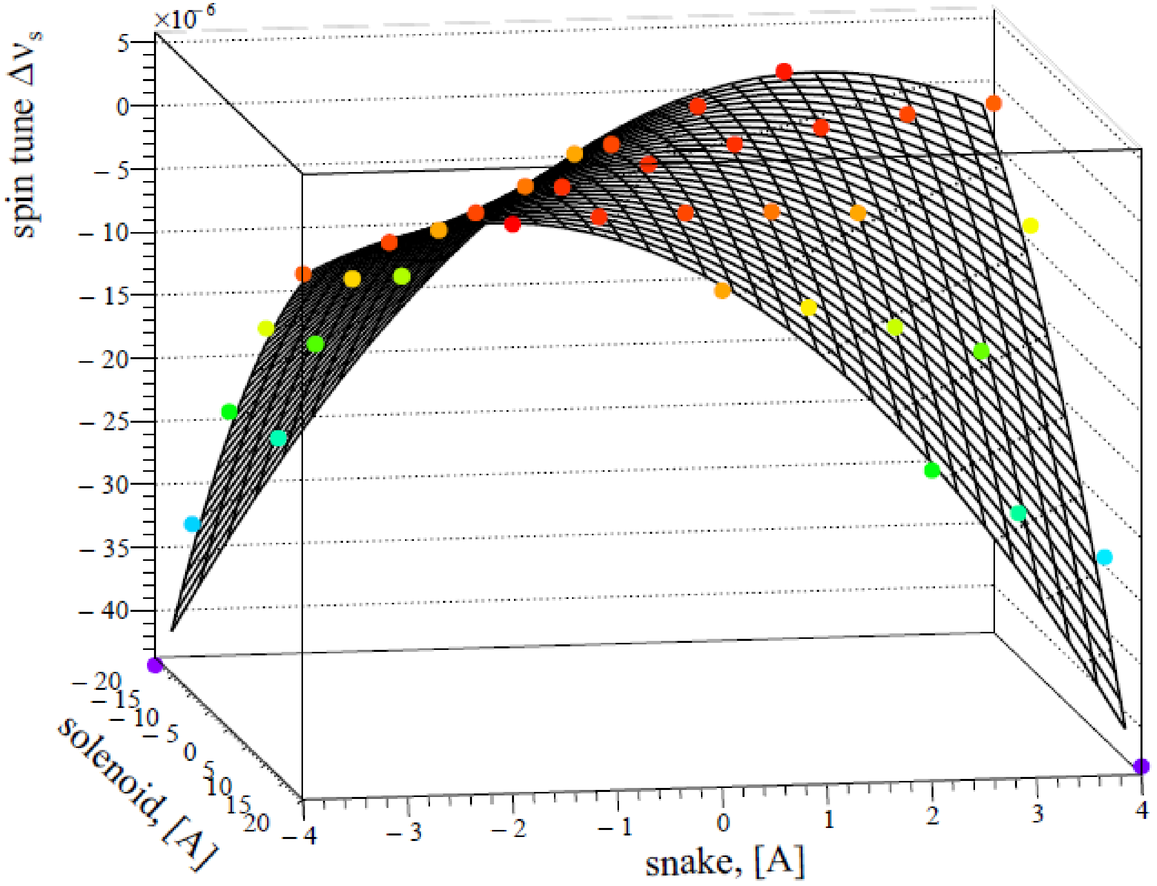
*Phys. Rev. Accel. Beams 20, 072801 (2017)

SPIN TUNE MAPS

- Position of saddle point is determined by the influence of the bump on the parameters c_{snake} and c_{sol}



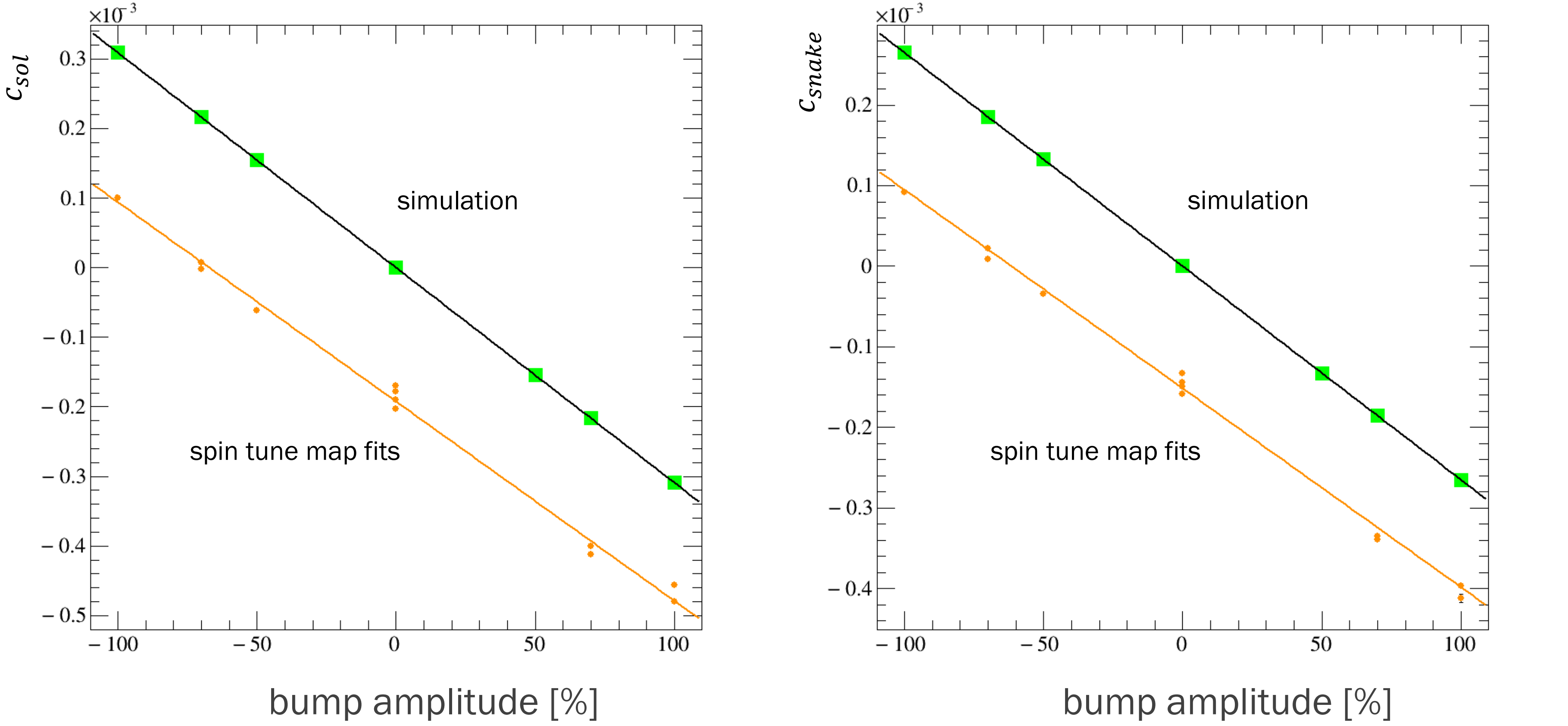
bump amplitude -3 mm



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:



$\sigma_c = 0.3\ \mu rad$, ->
$\sigma_d = 10^{-21} e \cdot cm$
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”:
- systematic contribution of MDM spin rotations into beam polarization, produced by inequality of two beam orbits, can be predicted and is under control to set EDM limit for deuterons at COSY $\sigma_d = 10^{-21} e \cdot cm$ for 100-s of beam storage cycle

- Outlook: the next stage of the experiment involves controlling the orbit excursion all over the ring by gradually scaling the field of all the vertical steerers down to zero, and observing the contribution of magnet alignment errors to the measured parameters c_{sol} and c_{snake}