Estimation of Systematic Errors for Deuteron Electric Dipole Moment (EDM) Search at a Storage Ring

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Outline

- Motivation and introduction to EDMs
- How can one measure the EDM of a charged particle?
- Simulations for systematic studies
- Experimental results overview
- Conclusion

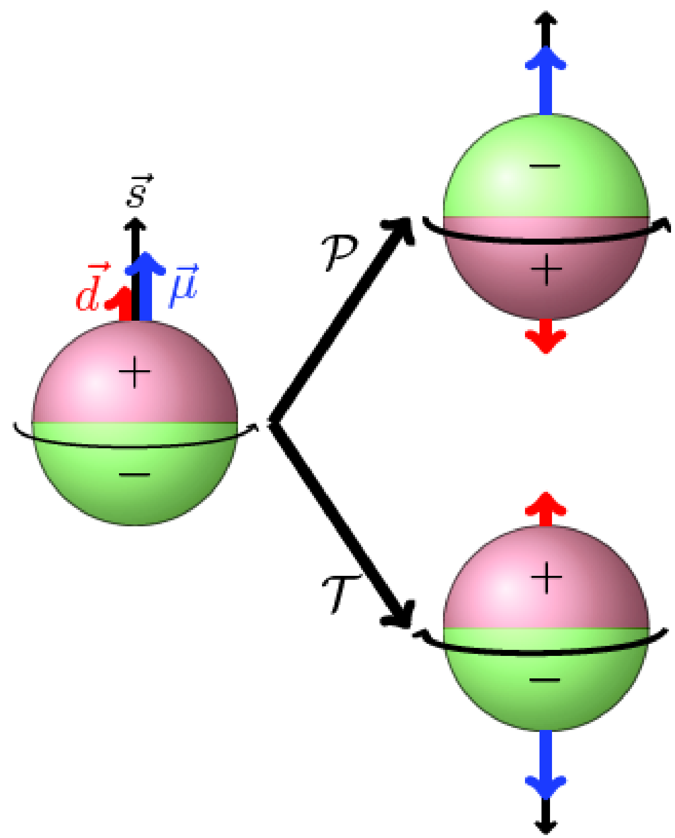
CP violation and EDMs

According to the Standard Model elementary particles (including hadrons) can only have non-vanishing EDMs, when parity and time invariances are violated!

$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

$$P: \quad H = -\vec{\mu}\cdot\vec{B} + \vec{d}\cdot\vec{E}$$

$$T: \quad H = -\vec{\mu}\cdot\vec{B} + \vec{d}\cdot\vec{E}$$



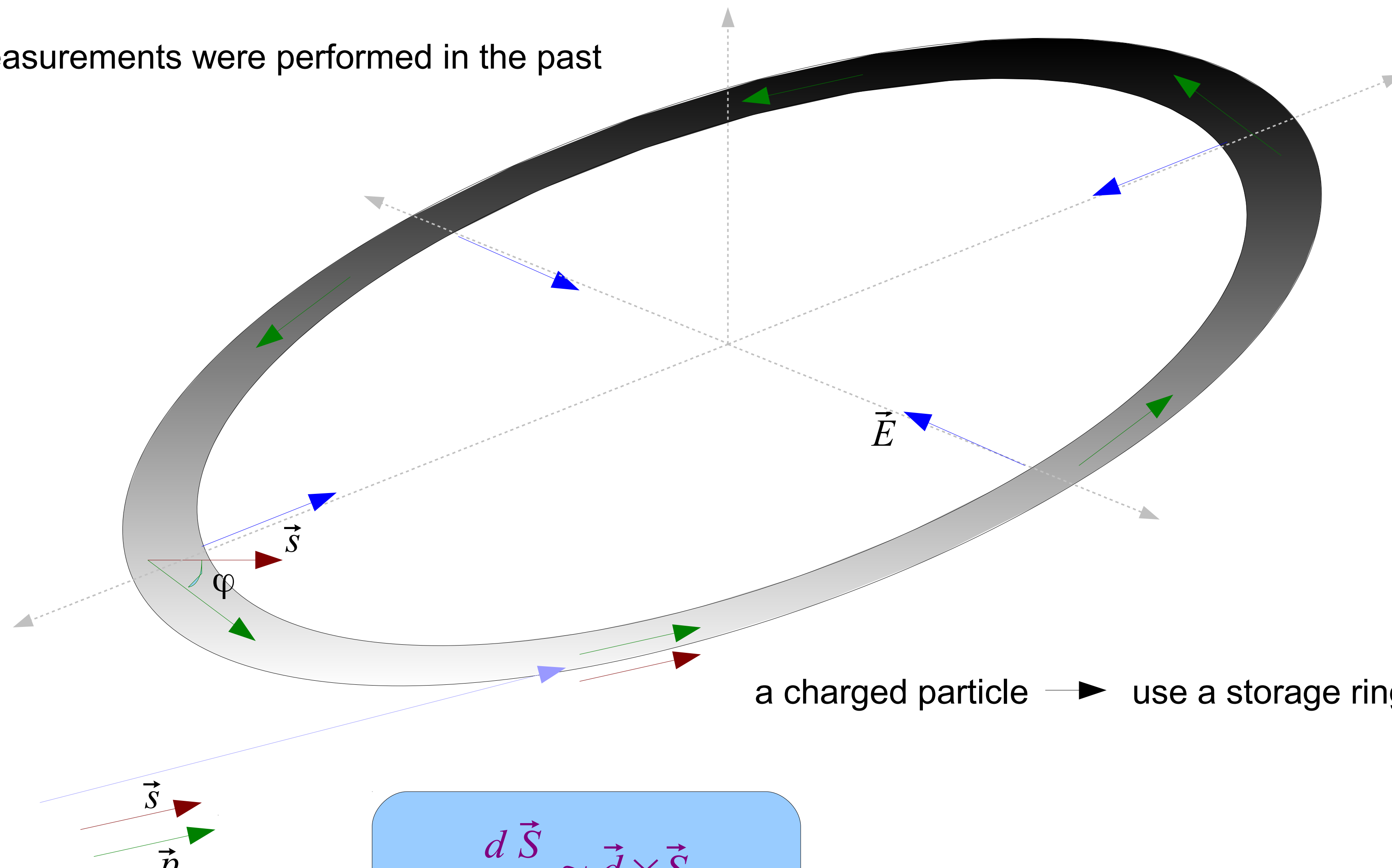
from J.Pretz

if CPT theorem holds, non-zero EDM violates CP

See the talks of A.Lehrach and A.Kacharava

How can one measure a charged particle EDM?

No direct measurements were performed in the past



a charged particle → use a storage ring

$$\frac{d\vec{S}}{dt} \sim \vec{d} \times \vec{S}$$

$$t \approx 1000\,s \rightarrow 1\,\mu\,rad$$

Thomas-BMT equation

Spin motion equation for relativistic particles in electromagnetic fields:

$$\frac{d\vec{S}}{dt} = \vec{S} \times \vec{\Omega}_{MDM} + \vec{S} \times \vec{\Omega}_{EDM}$$

$$\vec{\Omega}_{MDM} = \frac{e}{\gamma m}\left[G\gamma\vec{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{E}\times\vec{\beta}}{c} - \frac{G\gamma^2}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{B})\right]$$

$$\vec{\Omega}_{EDM} = \frac{e}{m}\frac{\eta}{2}\left[\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B} - \frac{\gamma}{\gamma+1}\vec{\beta}\left(\frac{\vec{\beta}\cdot\vec{E}}{c}\right)\right]$$

$$\vec{\mu} = 2(G+1)\cdot\frac{e}{2\mathrm{m}}\vec{S}$$

$$\vec{d} = \eta\cdot\frac{e}{2\mathrm{m}}\vec{S}$$

Spin tune:

$$\nu_s \approx \frac{|\Omega_{MDM}| + |\Omega_{EDM}|}{|\omega_{cyc}|} \approx \gamma G$$

$$\omega_{cyc} = \frac{e}{\gamma m}\vec{B}$$

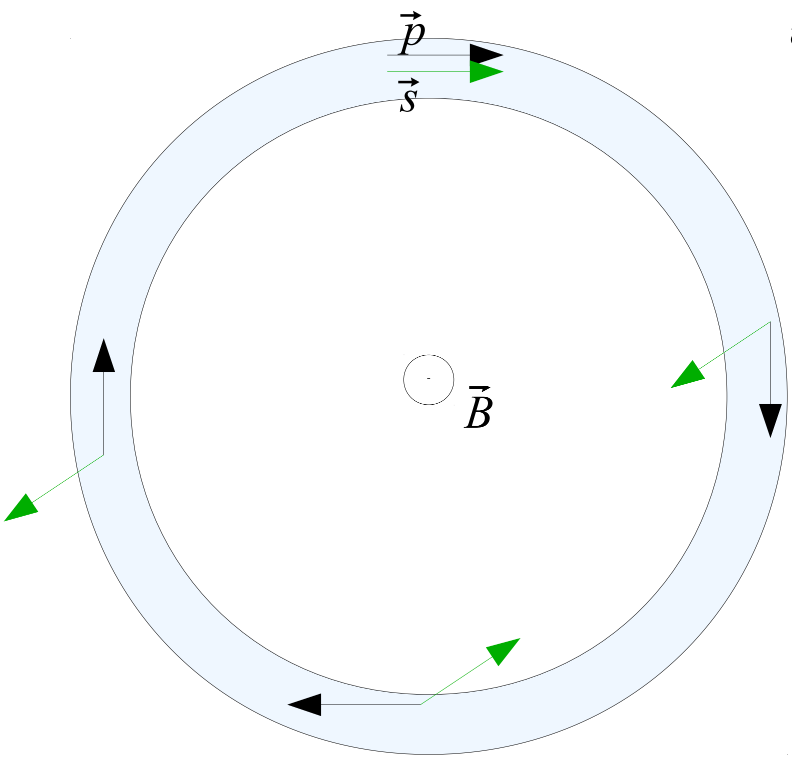
Deuteron: G = - 0.142561769

d = 10^{-29} e·cm: $\eta \sim 10^{-14}$

JÜLICH FORSCHUNGSZENTRUM

Pure magnetic ring:

$$\vec{\Omega} = \vec{\Omega}_{MDM} + \vec{\Omega}_{EDM} = \frac{e}{m}\left[G\vec{B} + \frac{\eta}{2}(\vec{\beta}\times\vec{B})\right]$$



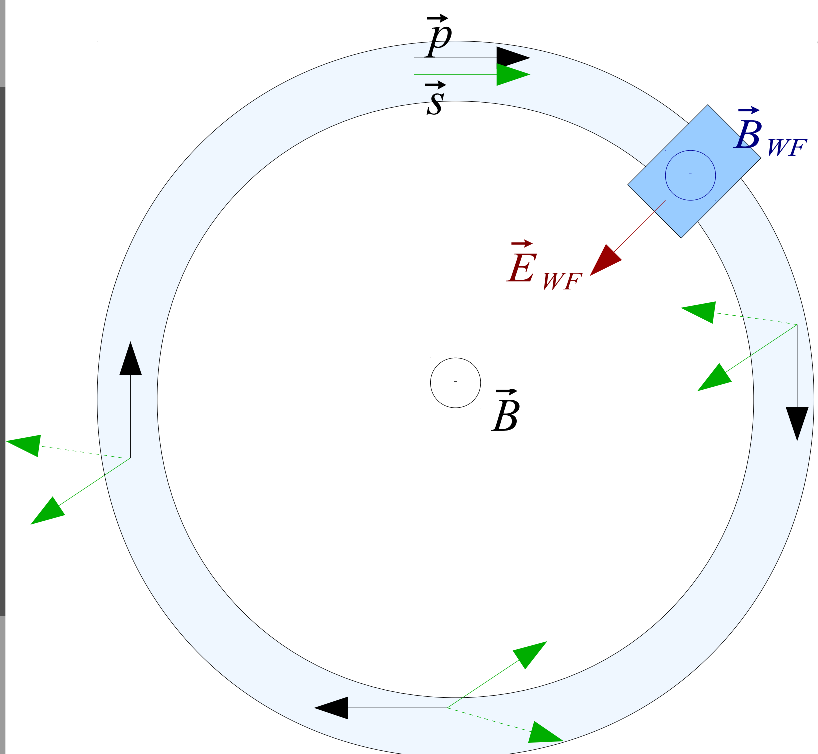
Half of the precession time spin is parallel to momentum and another half of the time it's antiparallel: no net EDM effect

See talk of S.Mey

RF Wien Filter approach

Pure magnetic ring:

$$\vec{\Omega} = \vec{\Omega}_{MDM} + \vec{\Omega}_{EDM} = \frac{e}{m}[G\vec{B} + \frac{\eta}{2}(\vec{\beta} \times \vec{B})]$$



Half of the precession time spin is parallel to momentum and another half of the time it's antiparallel: no net EDM effect

Use resonant Wien filter:

$\vec{E} + \vec{V} \times \vec{B} = 0$ Wien filter condition

Result:

- Particle trajectory is not affected
- Spin gets additional rotations and it stays parallel to momentum more than 50% of precession time

Net EDM effect can be observed

See talk of S.Mey

Spin tune modification by RF Wien Filter

Spin tune ν_s equals to number of spin turns with respect to the momentum per one ring revolution:

$$\nu_s \approx \frac{|\Omega_{MDM}| + |\Omega_{EDM}|}{|\omega_{cyc}|} \approx \gamma G$$

$$\omega_{cyc} = \frac{e}{\gamma m} \vec{B}$$

When the ring is purely magnetic and no misalignments are present then:

$$\vec{\Omega} = -\frac{e}{m}\left(G\vec{B} + \frac{\eta}{2}\vec{\beta} \times \vec{B}\right) = \Omega_R \frac{G\gamma}{\cos\xi} \vec{e}_x \cos\xi + \vec{e}_y \sin\xi,$$ where

$$\nu_s = \frac{G\gamma}{\cos\xi}$$ is the modified spin tune and:

$$\tan\xi = \frac{-\eta\beta}{G} \qquad \eta = \frac{d\,m}{e}$$

The EDM signal is proportional to tanξ

Simulation for RF Wien Filter with a perfect ring

RF Wien Filter properties:

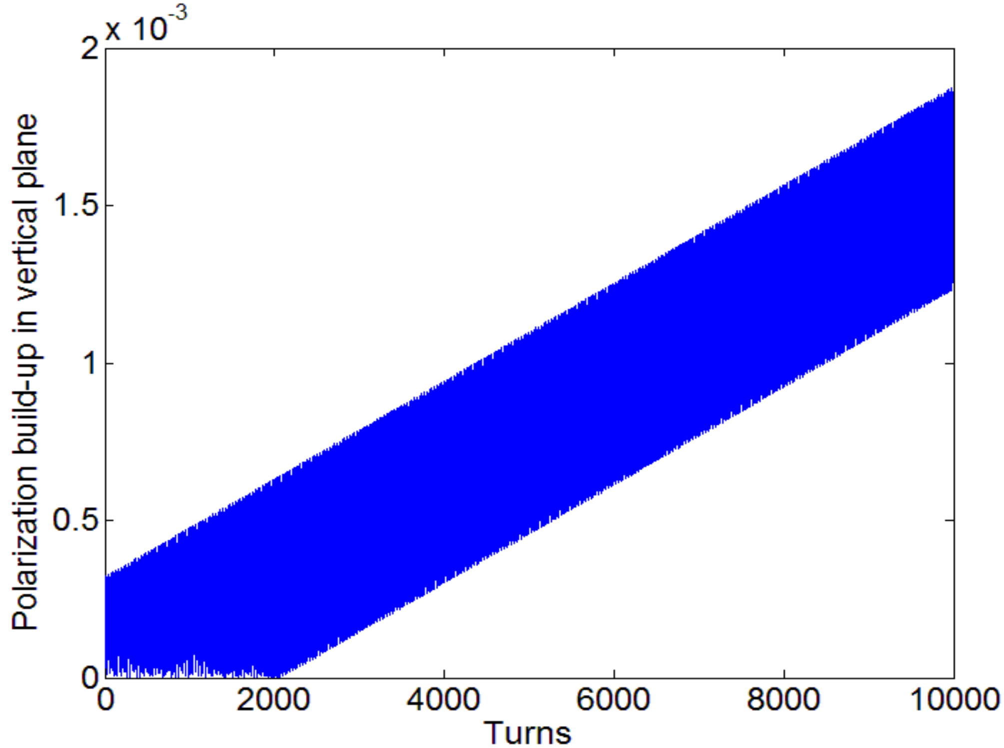
- E = 1 MV/m, B = 0.73 mT, L = 1m

Beam properties:

- $p_{deuterons}$ = 970 MeV/c, initial polarization was longitudinal, $\eta = 10^{-4}$ (d ~ 10^{-19} e·cm)

Simulation tool:

- MODE



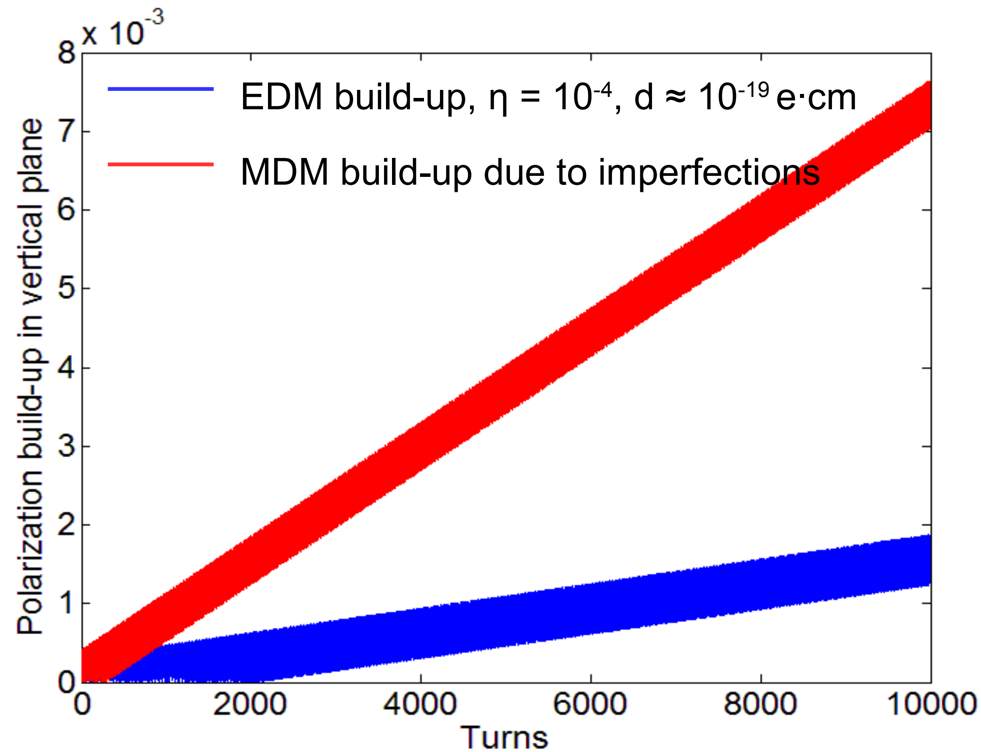
The EDM build-up per turn ~ 10^{-7}

The EDM tilts the spin precession axis, however imperfections act in the same way

Simulation for RF Wien Filter with an imperfect ring

Ring properties:

- Misalignments were randomly distributed:
  displacements with $\sigma = 10^{-4}$ meters
  rotations with $\sigma = 10^{-4}$ radians
  (typical configurations of COSY for uncorrected orbit)

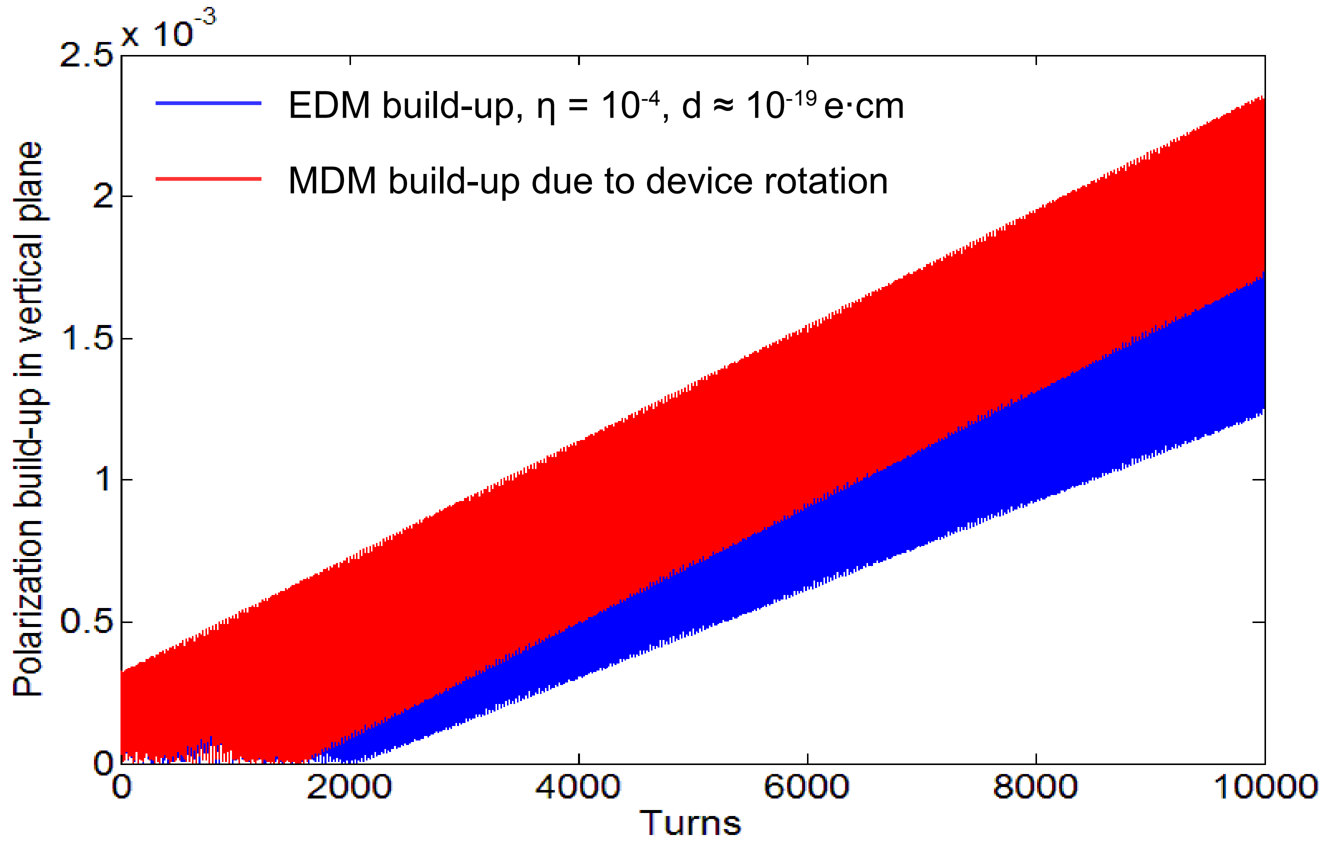


No orbit correction

The MDM build-up (due to interactions with imperfection fields) per turn ~ 10^{-7}
The MDM build-up line goes closer to EDM one when orbit is corrected
Orbit correction should be included into MODE for further studies

RF Wien Filter rotations around longitudinal axis I

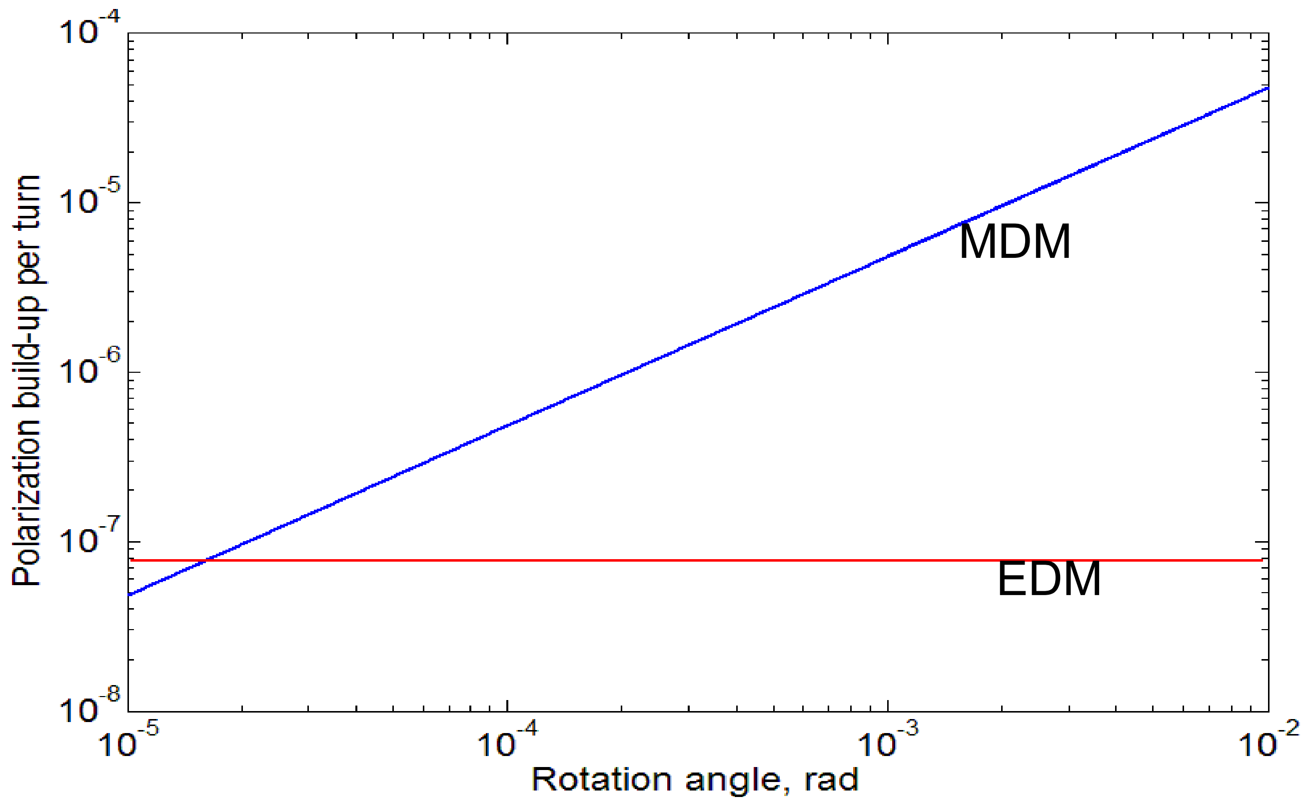
α – rotation angle = 10^{-4} rad.



RF Wien Filter rotations around longitudinal axis II

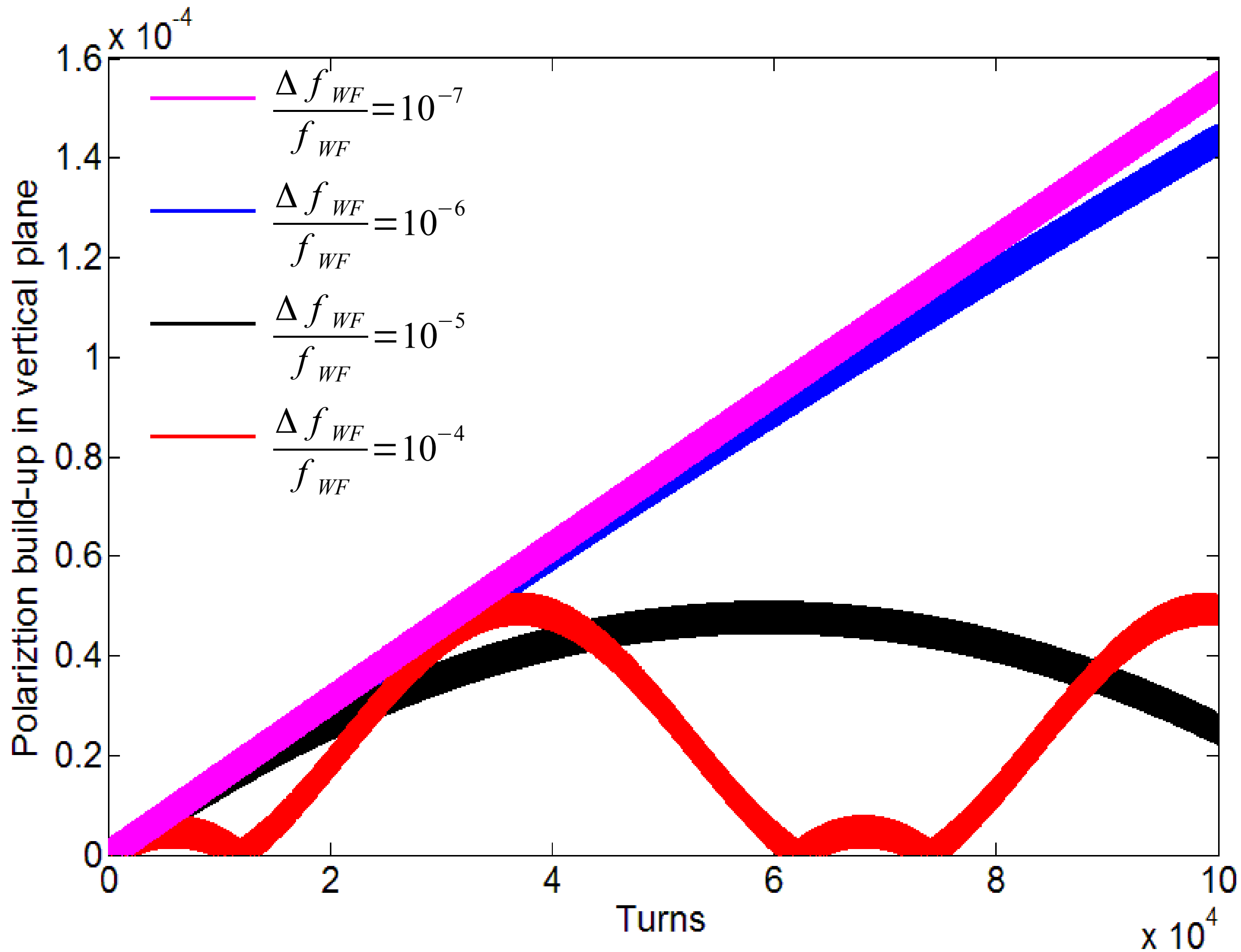
build-up due to EDM with $\eta = 10^{-4}$, $d \approx 10^{-19}$ e·cm for the perfect ring and no rotations

build-up due to MDM interactions caused by RF Wien Filter rotations



Frequency mismatch for RF Wien Filter

build-up due to EDM with $\eta = 10^{-6}$, $d \approx 10^{-21}$e·cm for the perfect ring and no rotations



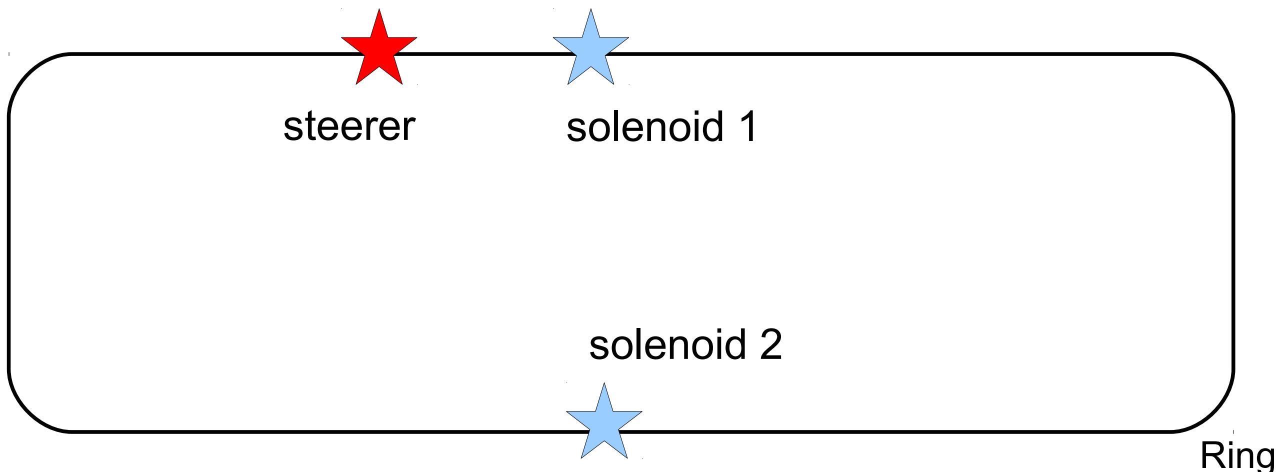
$f_s = f_{wf} \approx 125$ kHz

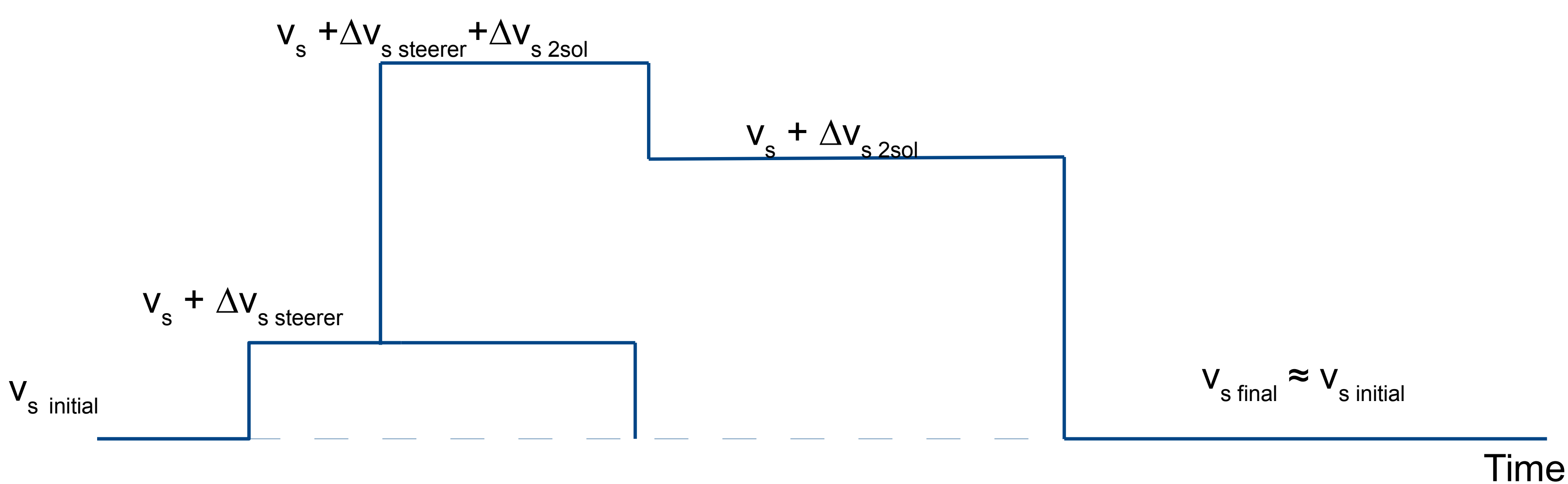
One should match and keep the frequency of RF Wien Filter with extraordinary precision during the storage

Systematic studies of ring imperfections at COSY, measuring relative changes of spin tune

- For the future experiment the studies of systematic errors arising from imperfections in the ring play crucial role
- Using the steerer kick we created an artificial imperfection in the ring. We could in detail explore it's impact on the spin motion with two solenoids

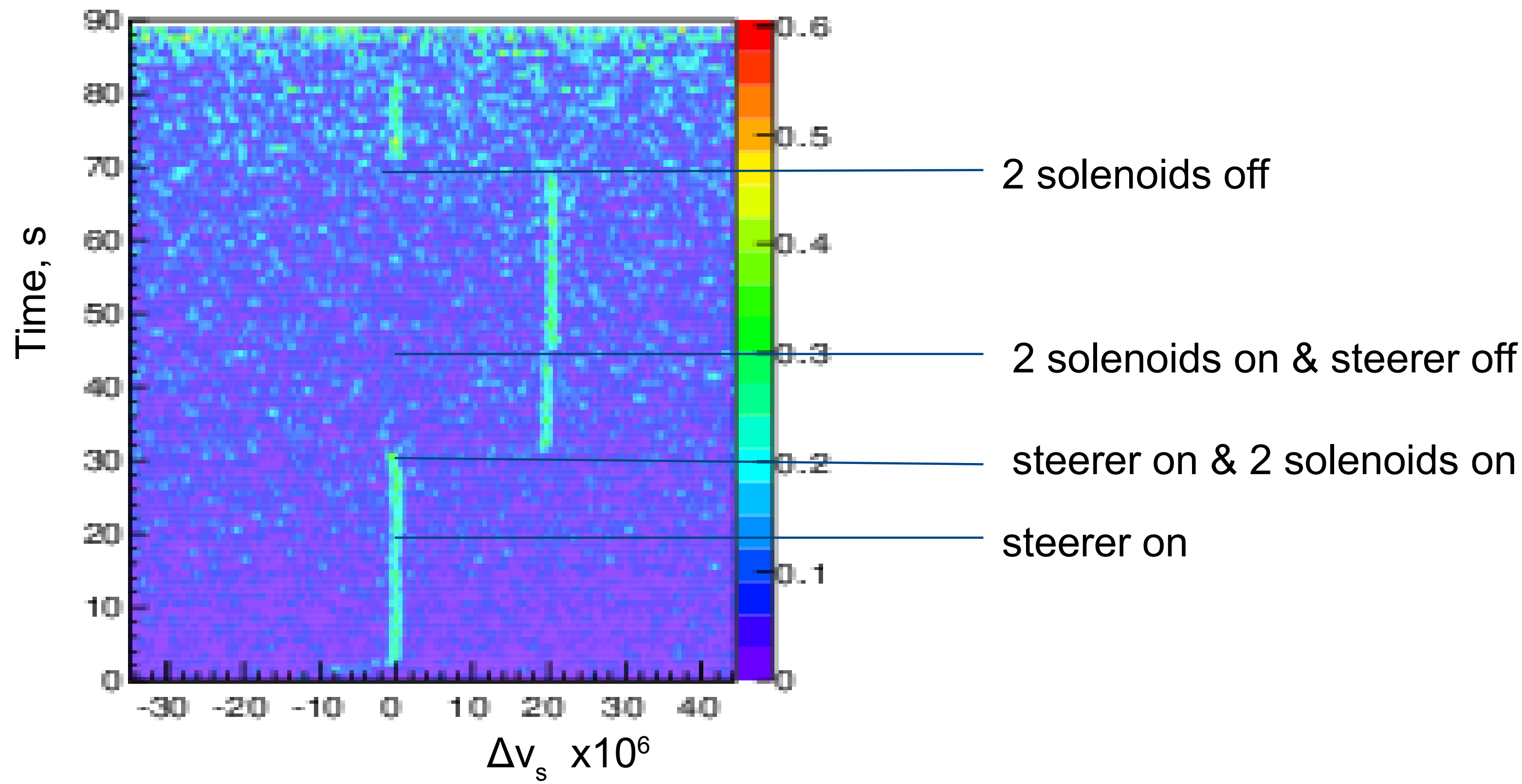
$B_{steerer} \approx 1mT$
$B_{sol} \approx 0.1$ mT





See the talk of A.Lehrach

Example of one measurement with fixed solenoid strengthes

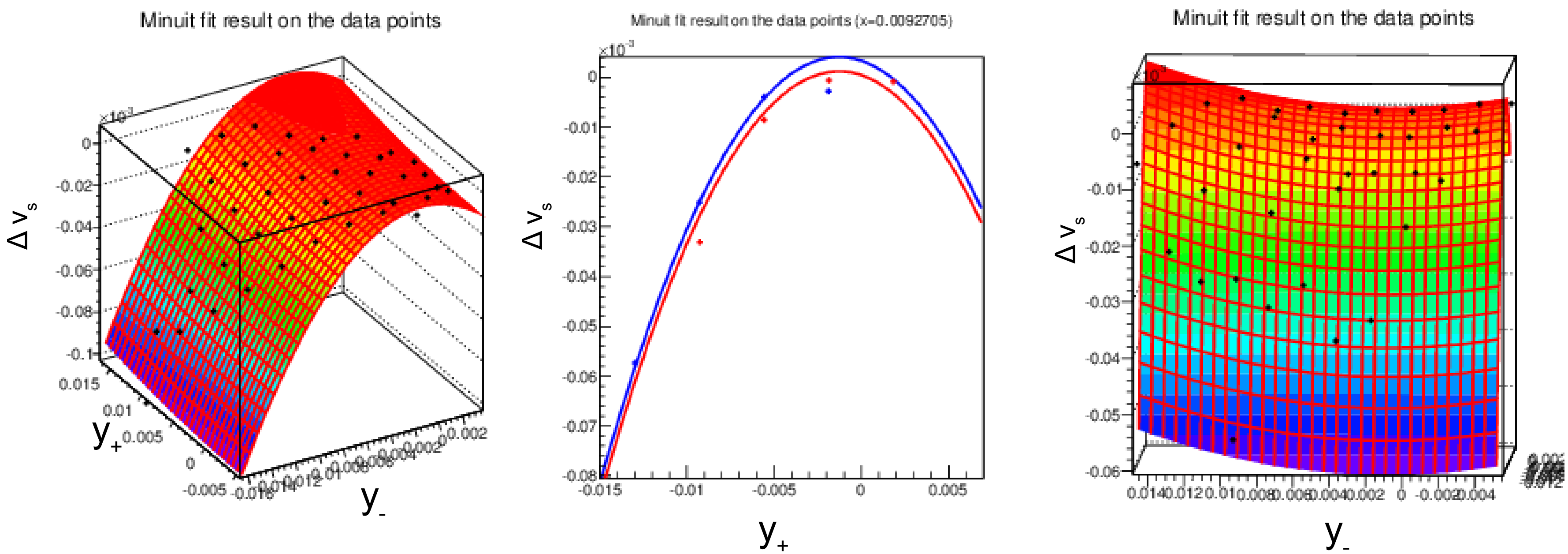


Quick online analysis:

Initial ν_s	$\Delta\nu_{s\ steerer}$	$\Delta\nu_{s\ steerer+2Sol}$	$\Delta\nu_{s\ 2Sol}$	Errors
0.1609718954	1.57 e-6	1.78 e-5	1.91 e-5	~ 5 e-8

Offline analysis gives an opportunity to determine the spin tune with precision of 10^{-10}

Spin tune maps
(preliminary results)



Spin tune map was build for the 2 solenoids + steerer case

$$y_{\pm} = \frac{\chi_1 \pm \chi_2}{2}$$

$\chi_{1,} \chi_2$ are solenoid kicks

Spin kicks from two solenoids at a saddle point characterise the integrated imperfection strength

Further analysis is on the way

See the talk of A.Saleev

Conclusions and future outlook

- EDMs of charged particles may be measured with storage ring experiments
- One can use RF Wien Filter in a pure magnetic ring in order to observe a build-up of an EDM signal due to interactions with motional electric field
- High precision of spin tune determination allows to investigate impact of misalignments on the spin motion
- The misalignments play crucial role in the experiment. MDM build-up for uncorrected orbit has the same order of magnitude as an EDM signal
- Orbit correction must be developed and implemented in MODE program
- Further simulations should be performed and compared with simulation results from COSY Infinity as well as with the experimental data

Backup

Thomas-BMT equation

“Frozen spin” method for pure electric ring:

$$\frac{d\vec{S}}{dt} = \vec{S} \times \vec{\Omega}_{MDM} + \vec{S} \times \vec{\Omega}_{EDM}$$

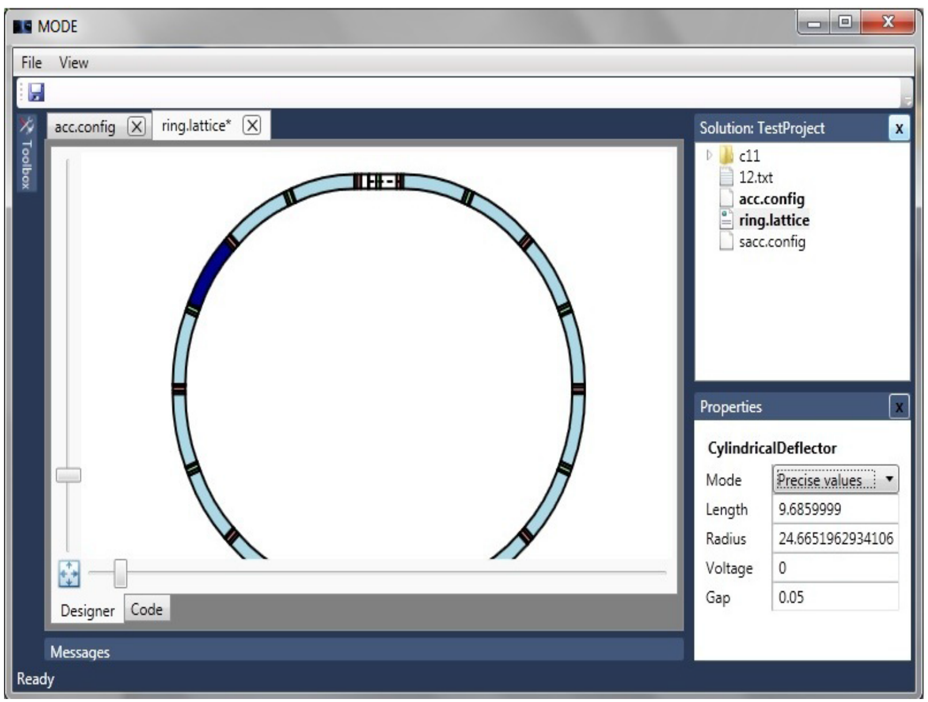
$$\vec{\Omega}_{MDM} \equiv 0 \text{ by doing the following} : (G - \frac{1}{\gamma^2 - 1}) = 0$$

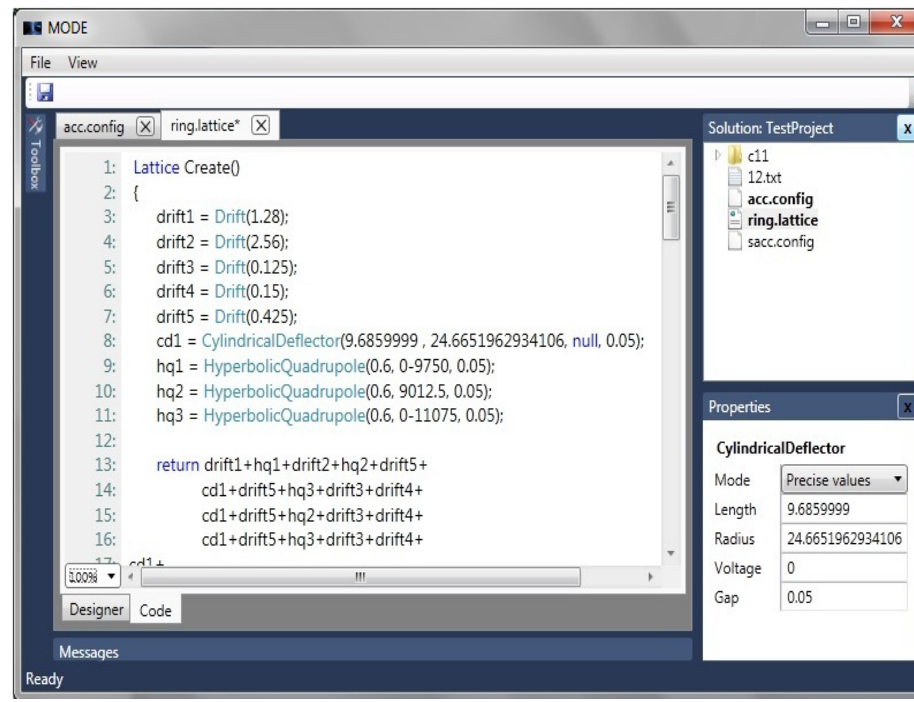
$$\vec{\Omega}_{EDM} = \frac{e}{m} \frac{\eta}{2} [\frac{\vec{E}}{c} - \frac{\gamma}{\gamma + 1} \vec{\beta} (\frac{\vec{\beta} \cdot \vec{E}}{c})]$$

Spin rotates with the same frequency as the momentum and stays parallel to it

Simulation tool

- MODE (Matrix integration of Ordinary Differential Equations) program was used to perform all the simulation
- The program allows building of high-order numerical matrix maps for spin-orbit dynamics in arbitrary distributed electro-magnetic fields





from A. Ivanov

Why is it important?

$$\eta = \frac{\eta_B - \eta_{\bar{B}}}{\eta_\gamma} = \begin{matrix} 6\cdot 10^{-10} & \text{observed} \\ 1\cdot 10^{-18} & \text{SM prediction} \end{matrix}$$

CP violation is needed to describe the difference (SM is not sufficient)

New sources of CP violation beyond the standard model are needed

Search for the presence of new physics