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 charge particle?
- Simulations for systematic studies
- Experimental results overview
- Conclusion

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Why is it important?

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

SM cannot fully describe the observations

New sources of CP violation beyond the standard model are needed

Search for the presence of new physics

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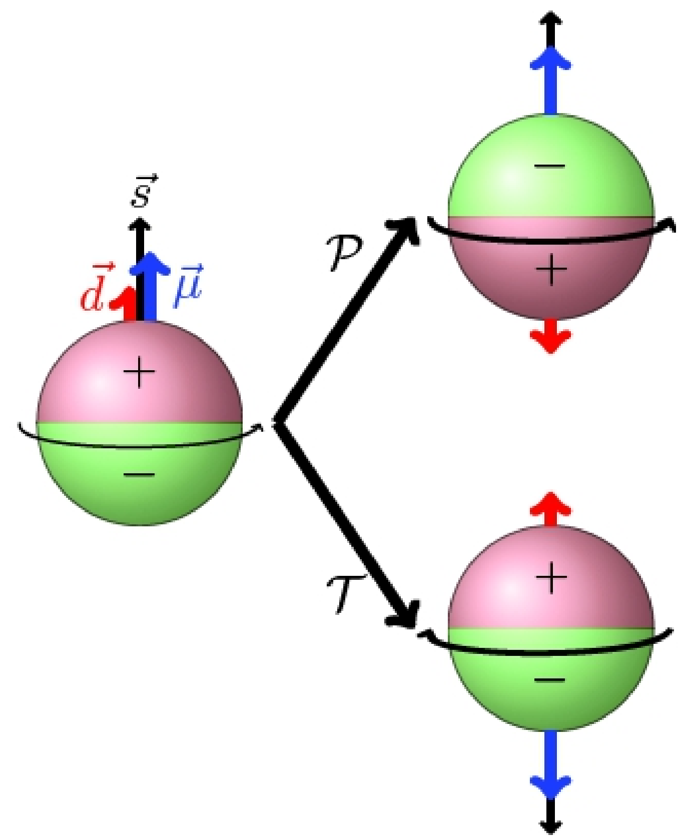
CP violation and EDMs

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 talks of A.Lehrach and A.Kacharava

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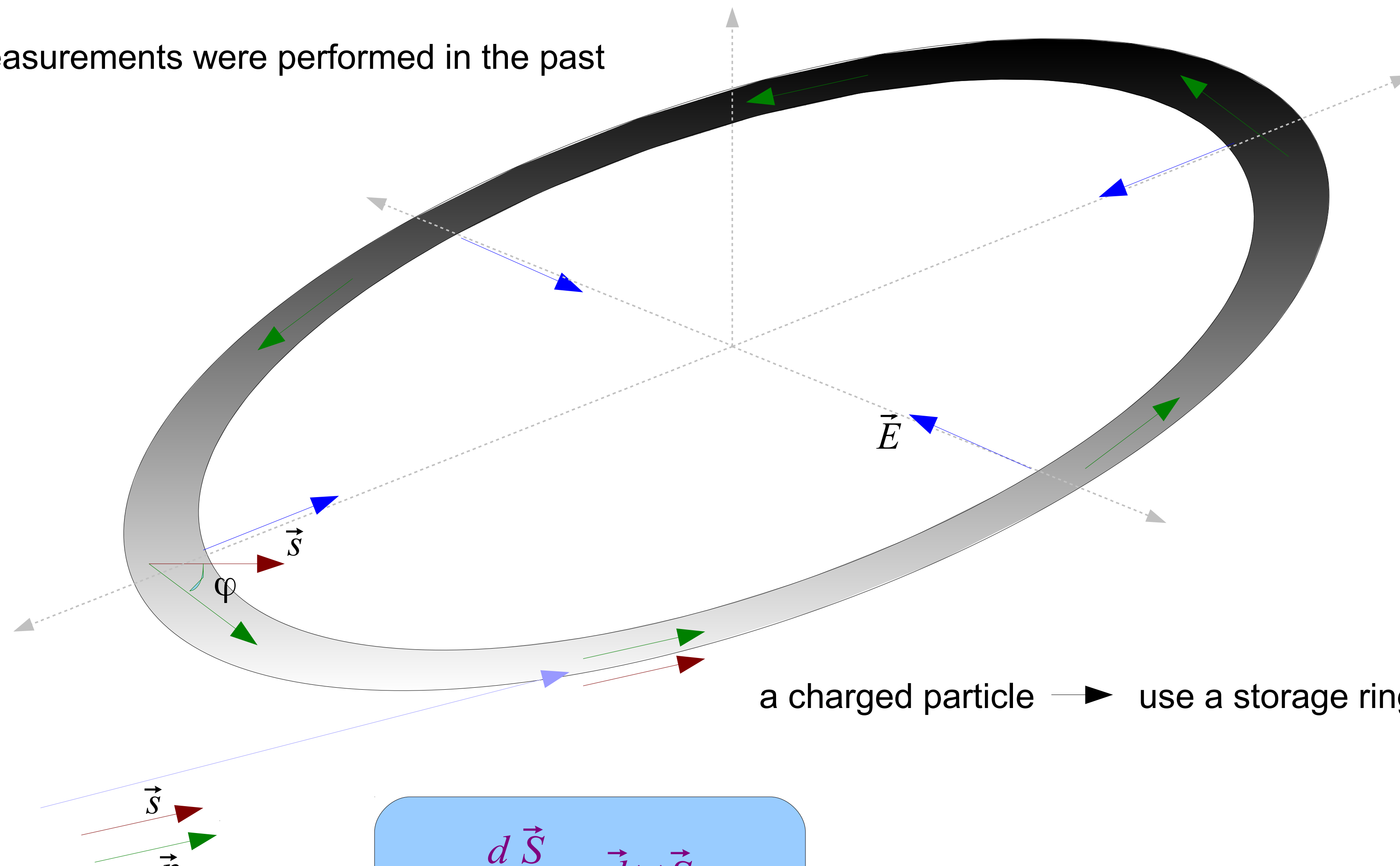
How can one measure a charged particle EDM?

No direct measurements were performed in the past



a charged particle → use a storage ring

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

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

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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:

$$\nu_s \approx \frac{|\vec{\Omega}_{MDM}| + |\vec{\Omega}_{EDM}|}{|\omega_{cyc}|} = \gamma G$$

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

Deuteron: G = - 0.142561769

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

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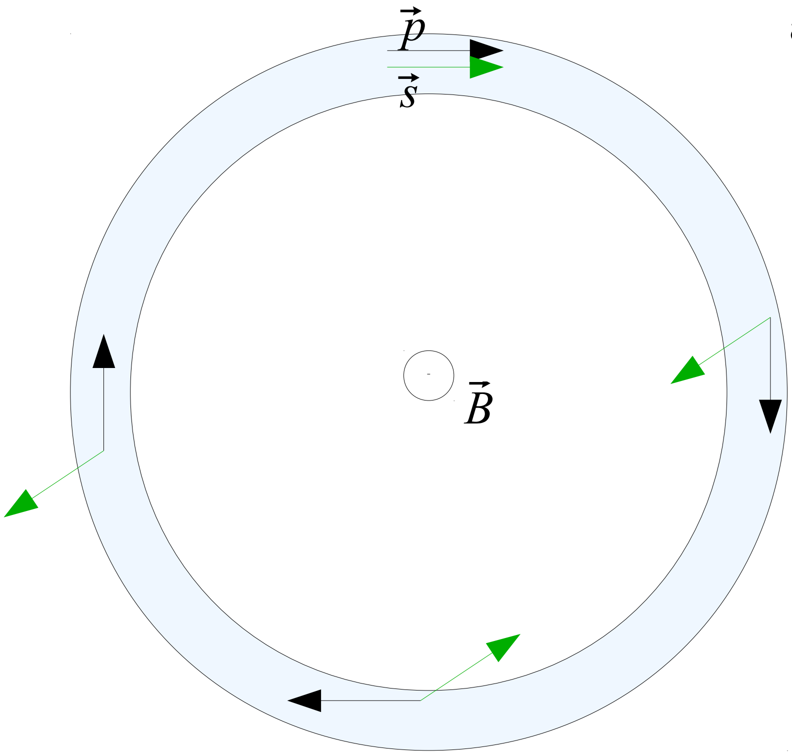
RF Wien Filter approach

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

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RF Wien Filter approach

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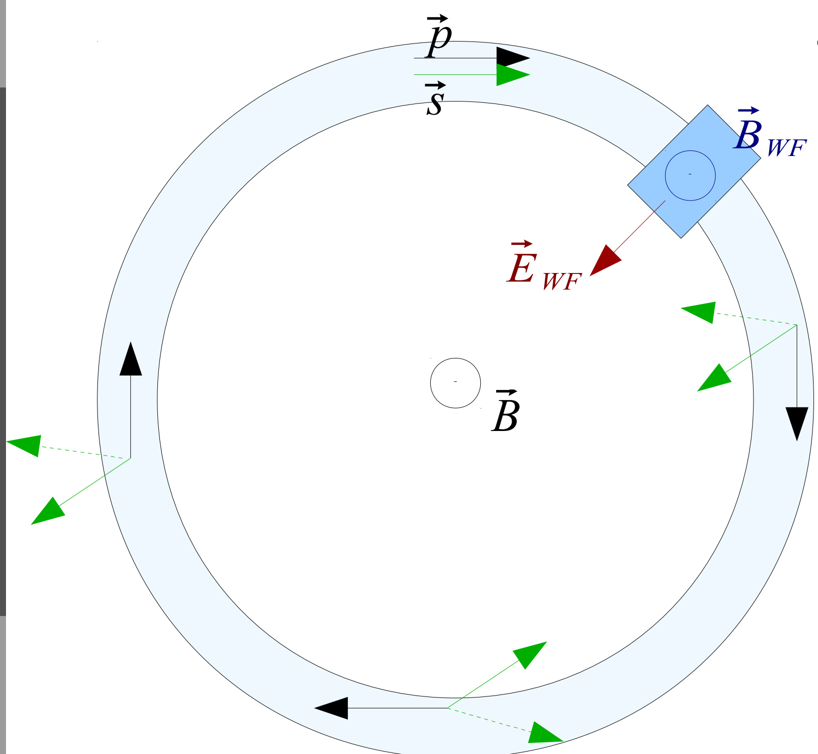

Half of the precession time spin is parallel to momentum and another half of the time it's antiparallel: no net EDM effect

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

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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:

$$\nu_s \approx \frac{\left|\vec{\Omega}_{MDM}\right| + \left|\vec{\Omega}_{EDM}\right|}{|\omega_{cyc}|} = \gamma G$$

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

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:

$$\tan\xi = \frac{-\eta\beta}{G} \qquad \eta = \frac{dm}{e}$$

The EDM signal is proportional to tanξ

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Simulation for RF Wien Filter with a perfect ring

RF Wien Filter properties:

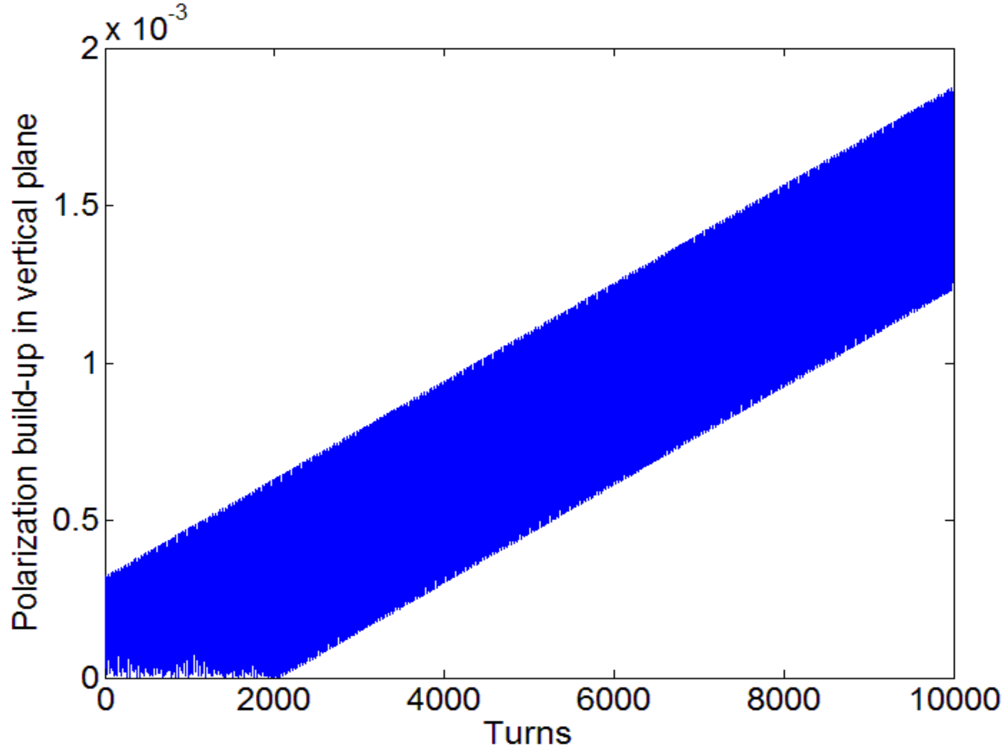
- E = 1 MV/m, B = 0.73 mT, L = 1m

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 second ~ 10^{-7}

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

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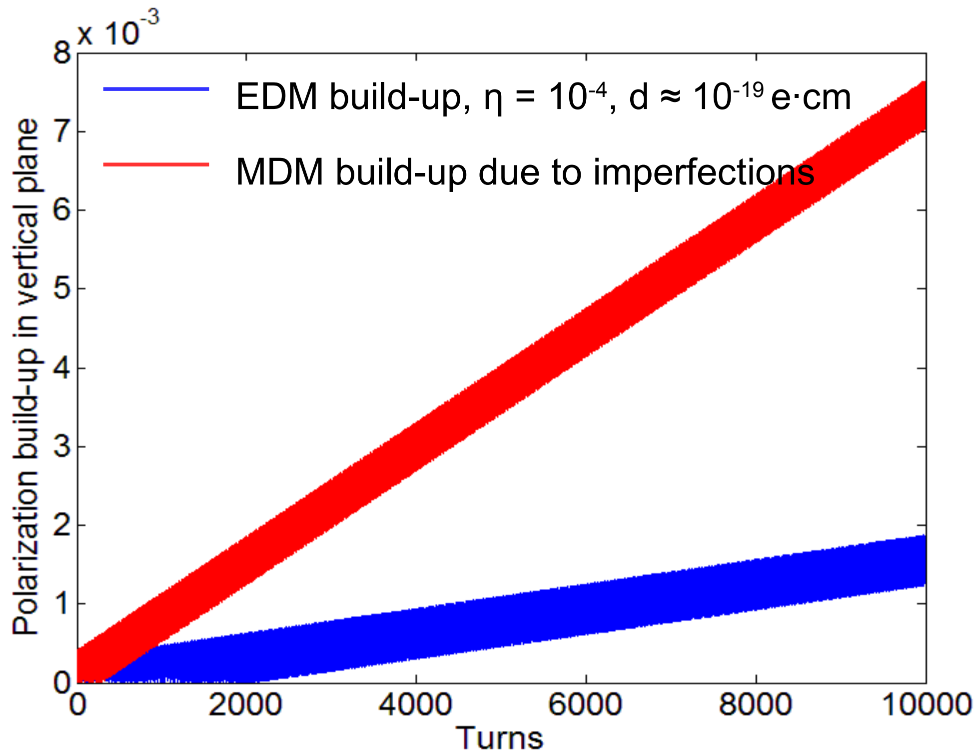
Simulation for RF Wien Filter with an imperfect ring

Ring properties:

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



The MDM build-up (due to interactions with imperfection fields) per second ~ 10^{-7}

EDM limit ≈ 10^{-19} e·cm

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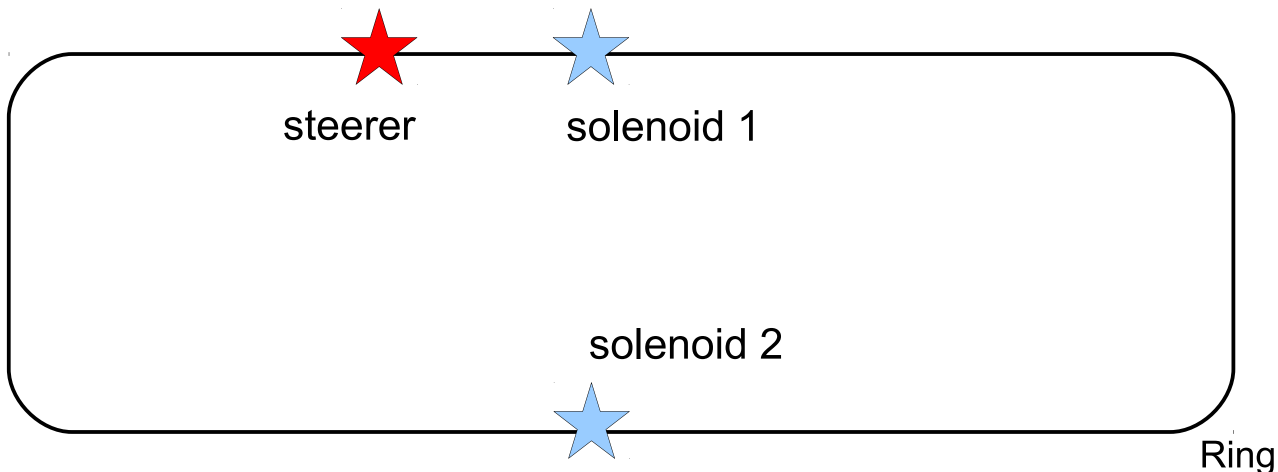
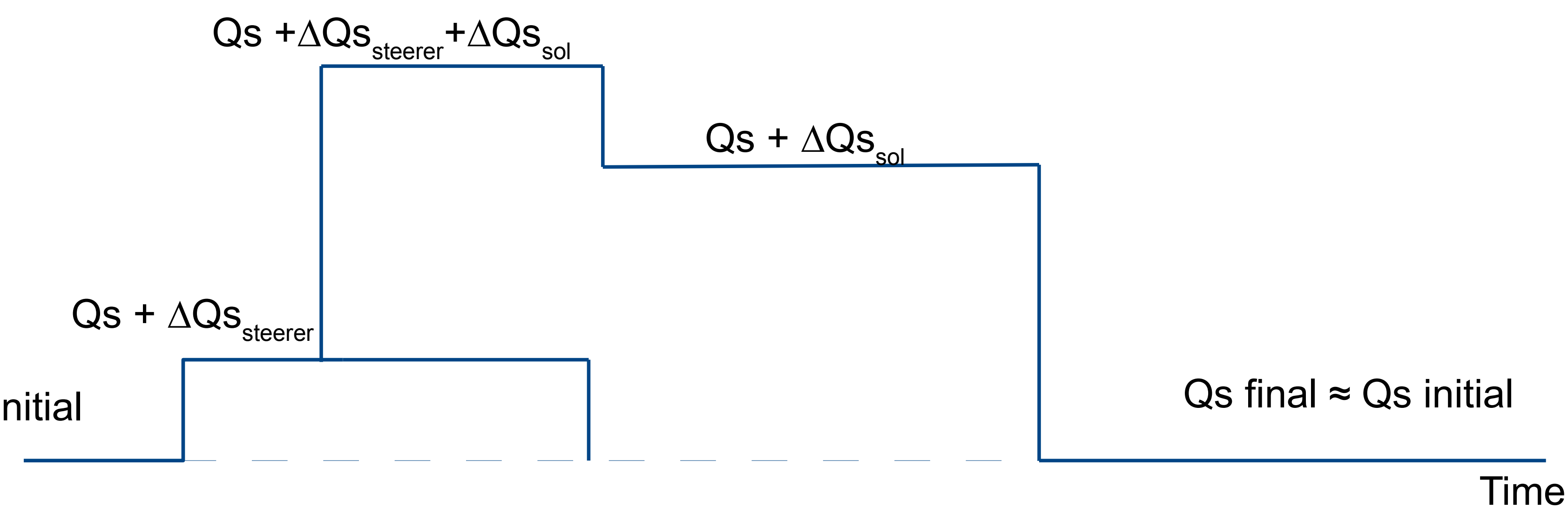
Systematic studies of ring imperfections at COSY

- 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

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





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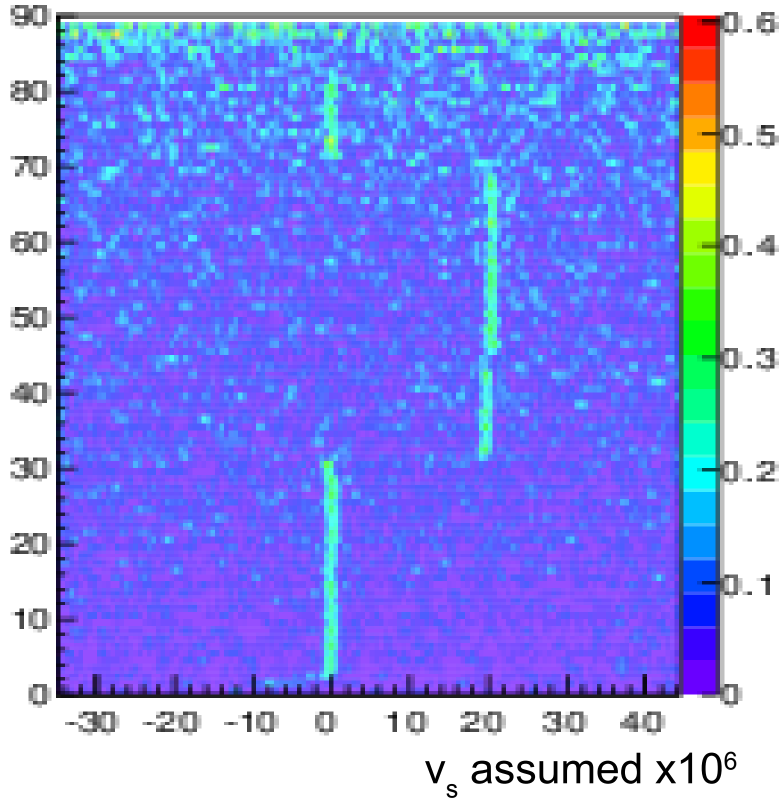
Spin tune as a tool for precision measurements



Quick online analysis:

Initial ST	$\Delta ST_{steerer}$	$\Delta ST_{Steerer + 2 Sol}$	$\Delta ST_{2 Sol}$	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 spin tune with precision of 10^{-10}

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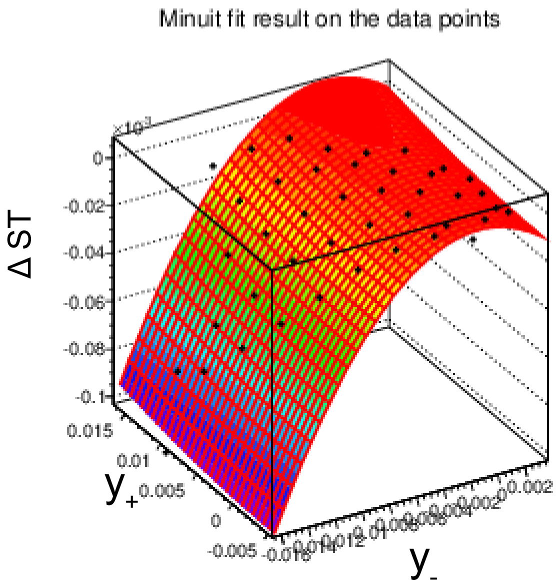
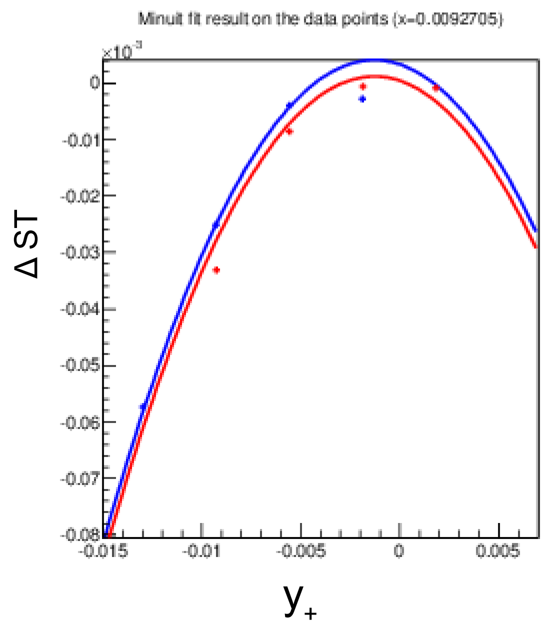
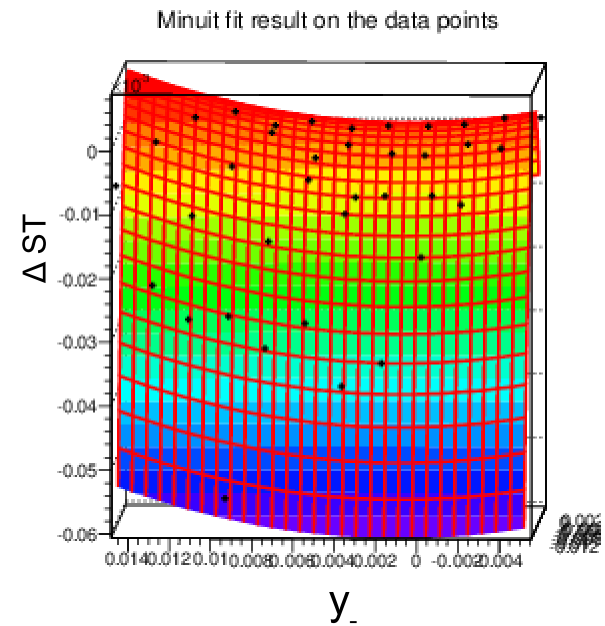
Spin tune maps (preliminary results)







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

Using the information how the sadle point position was changed, one can calculate the spin kick of the imperfection: $\xi_{steerer} = 5.83 \cdot 10^{-3}$ rad

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Conclusions

- 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
- With current system for orbit correction and the alignment precision one can get a systematic limit on deuteron EDM of the order of 19^{-19} e·cm at COSY

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Thank you

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Backup

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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

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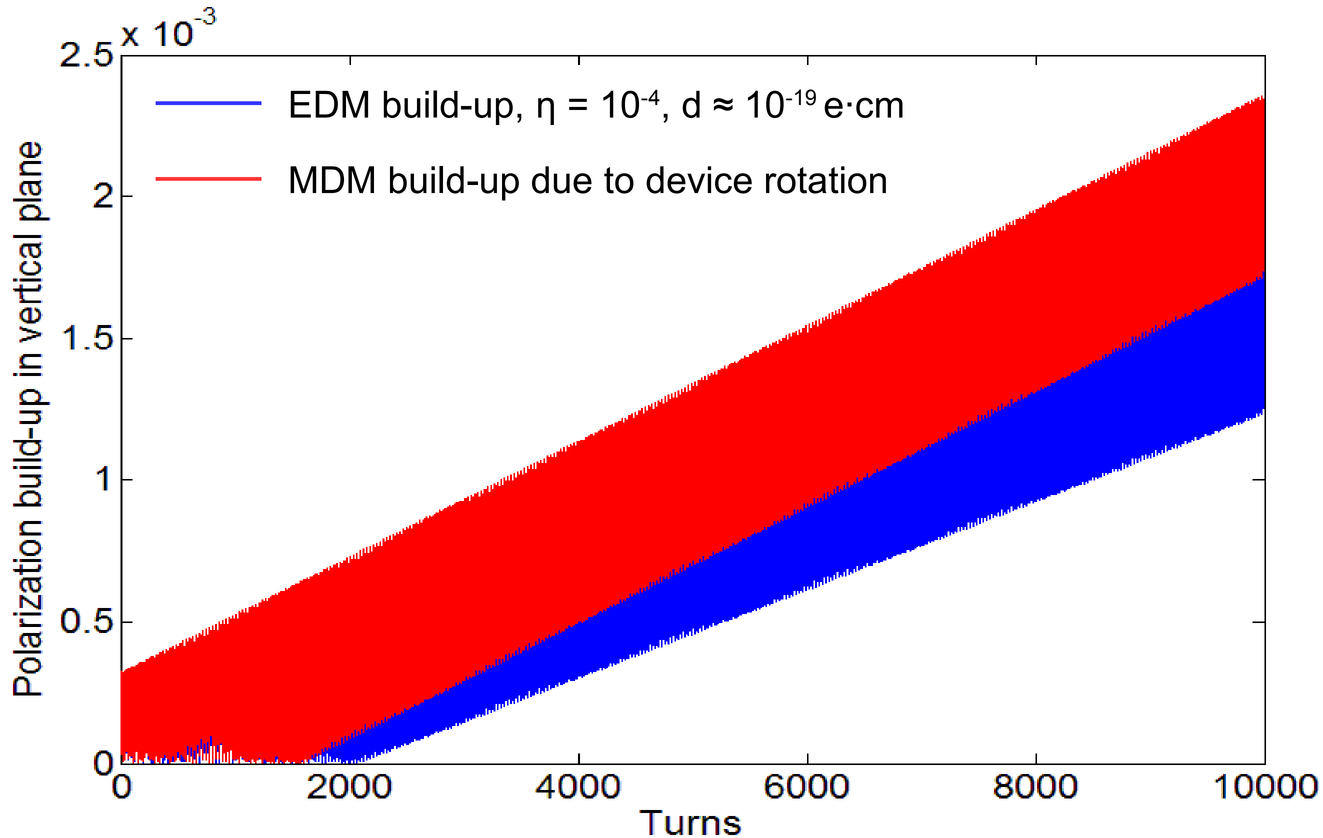
Simulation for RF Wien Filter with an imperfect ring

α – rotation angle = 10^{-4} rad.



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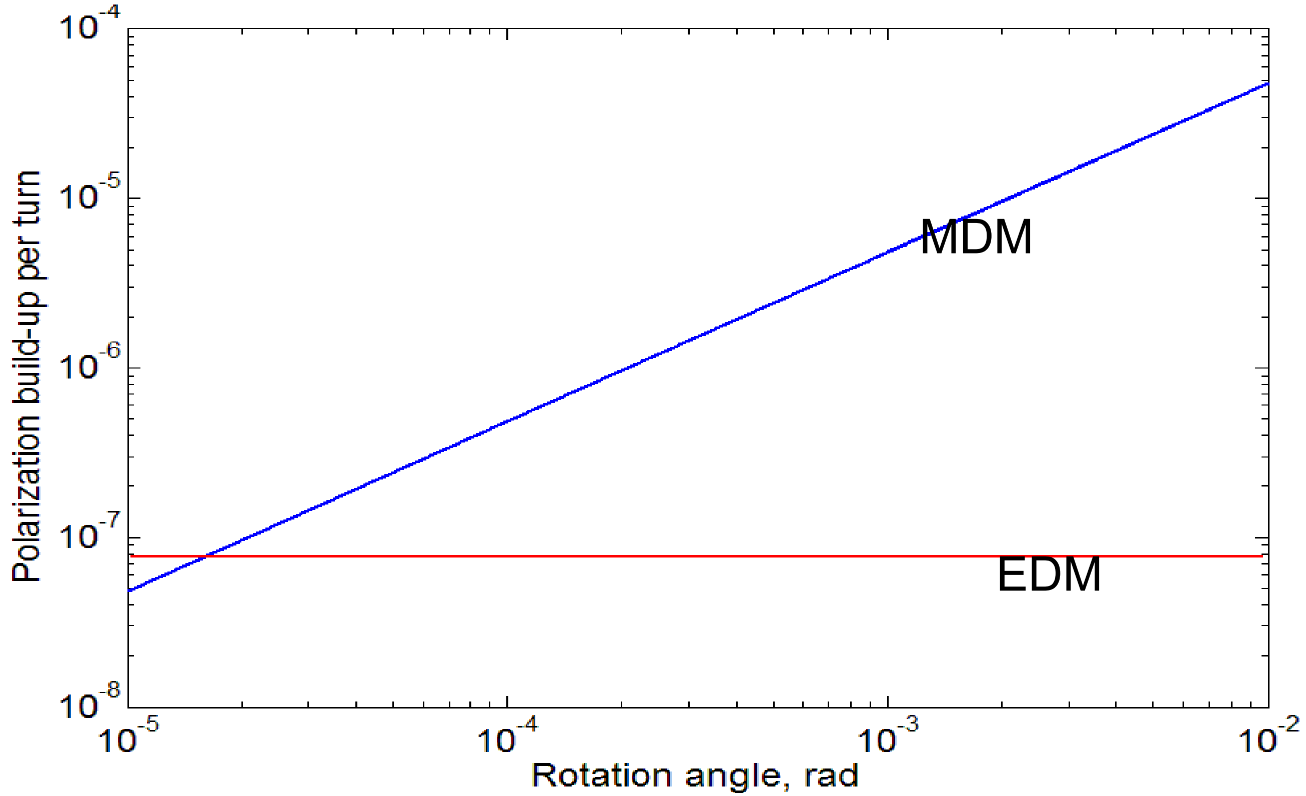
Wien Filter rotations around longitudinal axis II

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



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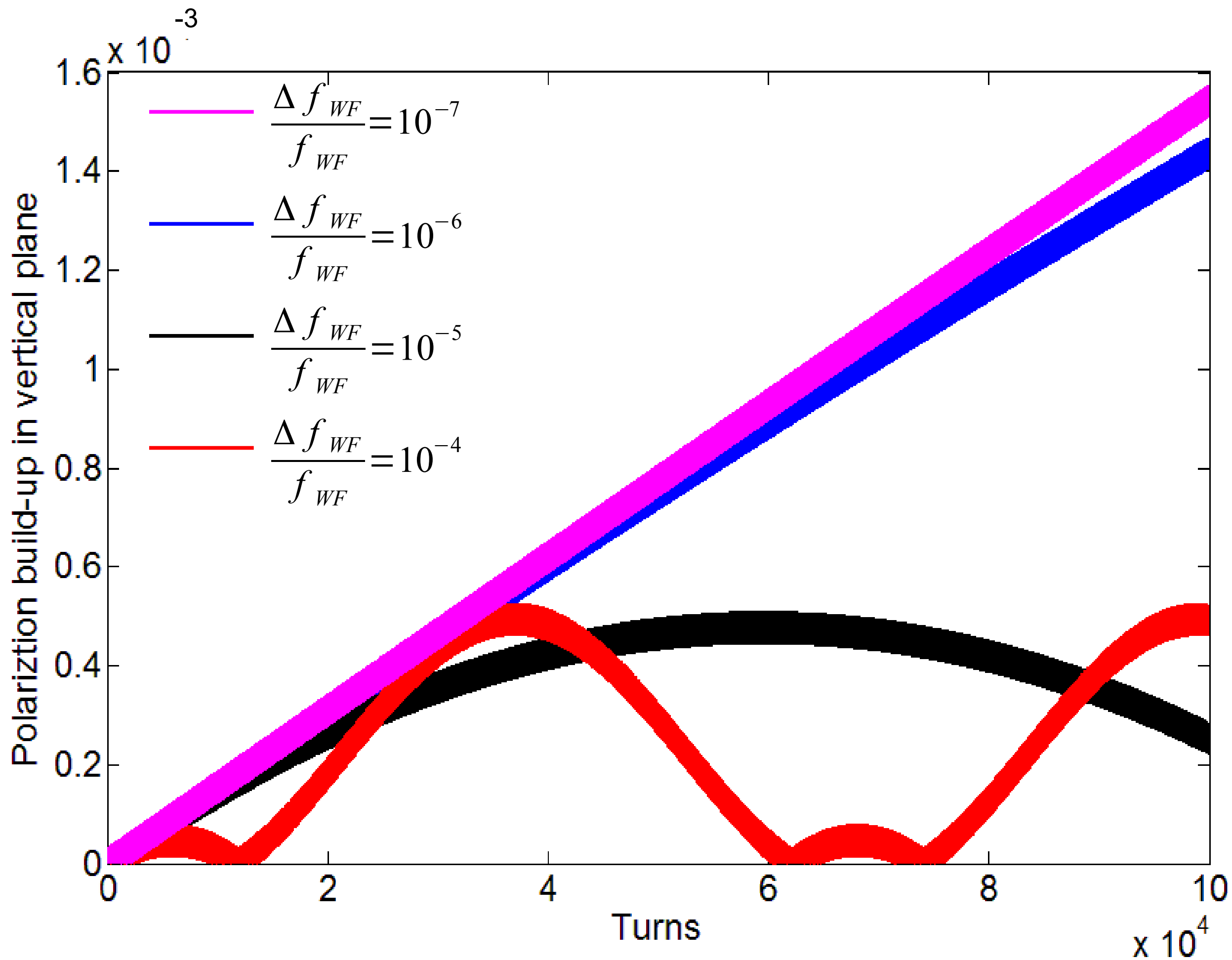
Frequency mismatch for RF Wien Filter

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



$f_s = f_{wf} \approx 120$ kHz

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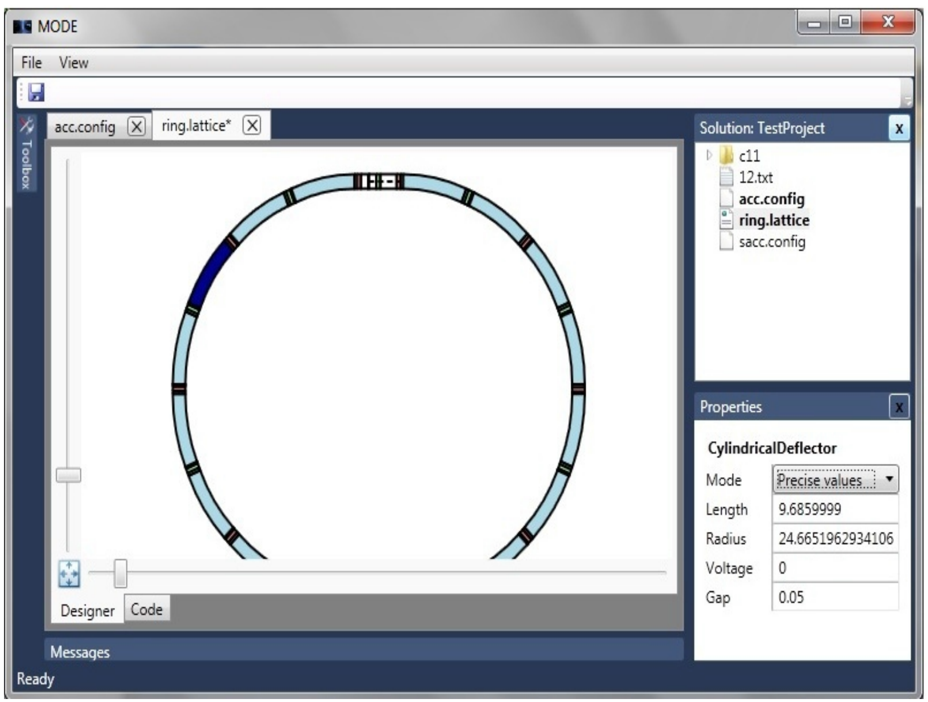
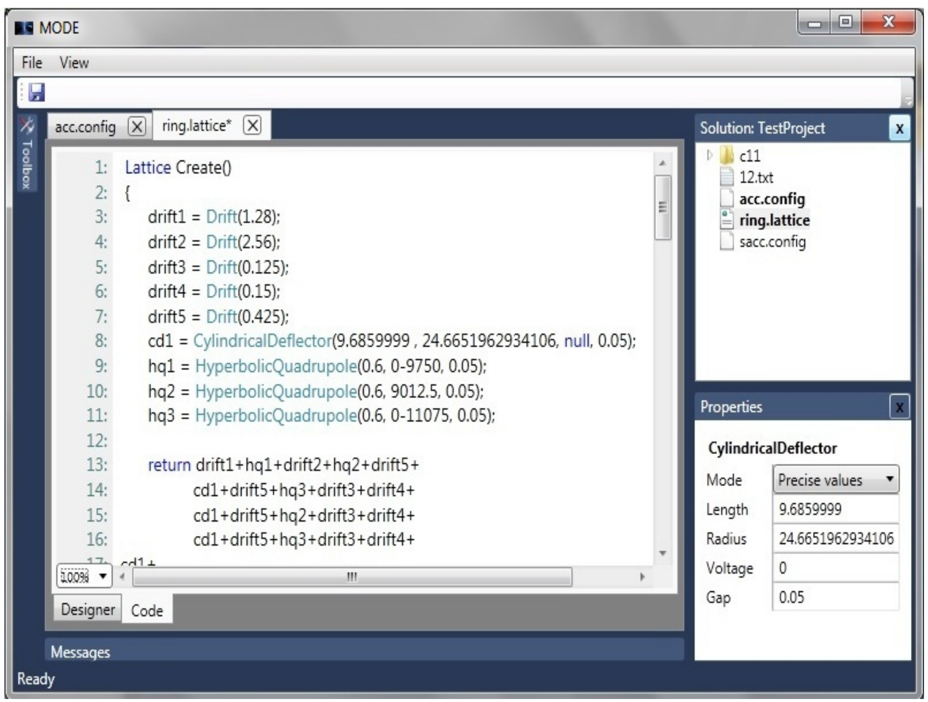
Simulation tool

- 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

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