Physics
Institute III B

RWTH AACHEN UNIVERSITY

JEDI

JÜLICH
FORSCHUNGSZENTRUM

Investigation of Beam and Spin Dynamics for EDM Measurements at COSY

2014-09-04 | Marcel Rosenthal on behalf of the JEDI Collaboration

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Outline

- **Part 1: Introduction**
  - What are Electric Dipole Moments?
  - General idea for EDM measurements in storage rings
  - The Cooler Synchrotron COSY, Jülich
  - Thomas-BMT-equation

- **Part 2: Simulations**
  - Simulation framework
  - Measurement principle at COSY, Jülich
  - Spin Coherence Time studies
  - False signal due to magnet imperfections

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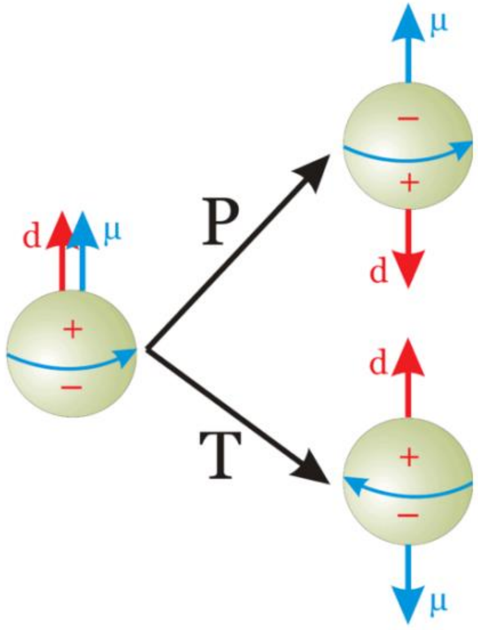
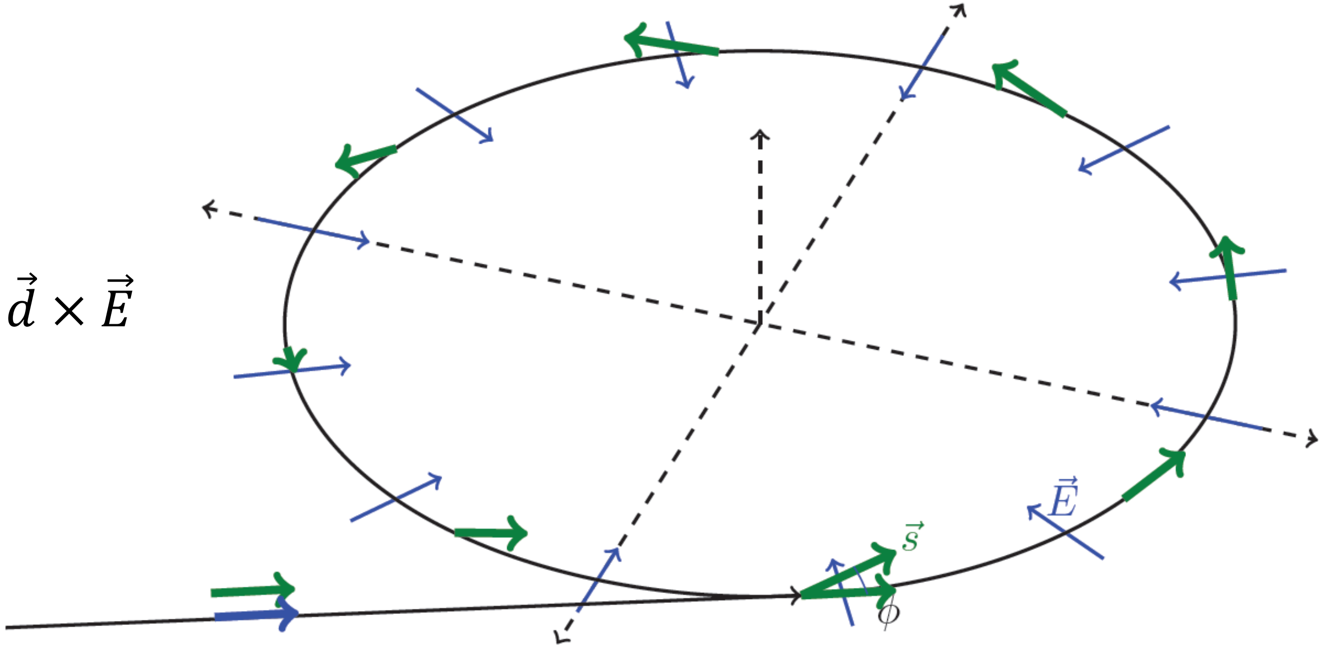
CP-Violating permanent EDMs



- Electric Dipole Moments:
  - Charge separation
  - Fundamental property
- Permanent EDMs are P- and T-violating
  - CPT-Theorem: CP-Violation
- Known CP-Violation not sufficient to explain Matter-Antimatter-Asymmetry in universe
- Search for new sources of CP-Violation (Θ-term, BSM) by measuring Electric Dipole Moments of charged hadrons in storage rings

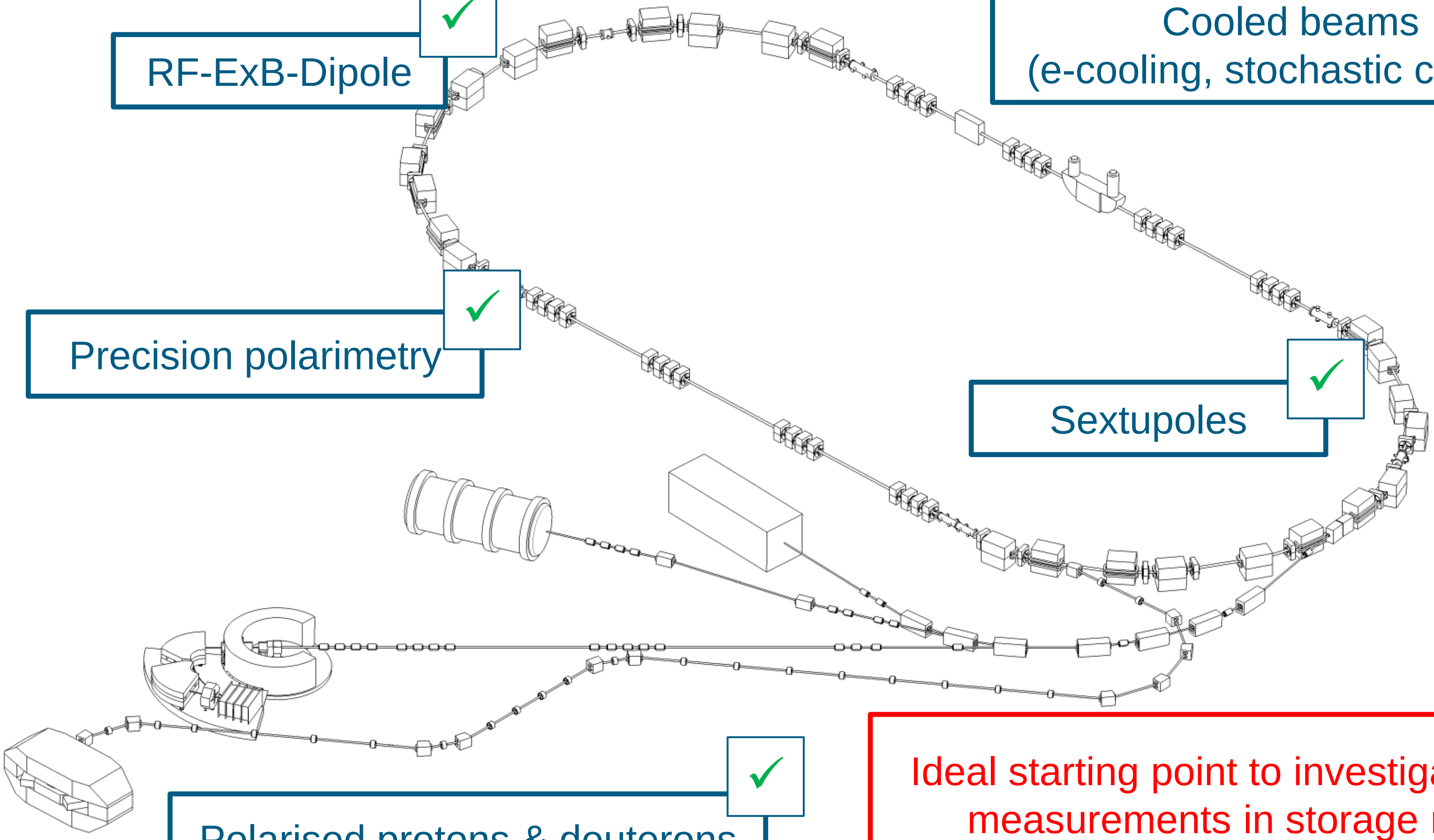
EDM measurements in storage rings

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} \propto \vec{d} \times \vec{E}$$



- General idea:
  - Inject polarised particles with spin pointing towards momentum direction
  - *„Frozen Spin“*-Technique: without EDM spin stays aligned to momentum
  - EDM couples to electric bending fields
  - Slow buildup of EDM related vertical polarisation

The Cooler Synchrotron COSY



RF Solenoid ✓

RF-ExB-Dipole ✓

Cooled beams
(e-cooling, stochastic cooling) ✓

Precision polarimetry ✓

Sextupoles ✓

Polarised protons & deuterons ✓

Ideal starting point to investigate EDM measurements in storage rings.

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Thomas-BMT-Equation

- Equation of spin motion for relativistic particles in electromagnetic fields:

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

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

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

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

	G
Proton	1.792847357
Deuteron	-0.142561769

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

d	η
10^{-24} e cm	$\sim 10^{-9}$
10^{-29} e cm	$\sim 10^{-14}$

Thomas-BMT-Equation (pure magnetic)

- Equation of spin motion for relativistic particles in electromagnetic fields:

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

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

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

- Cooler Synchrotron Jülich is conventional pure magnetic ring:
  - Spin precesses around vertical guiding field.
  - Number of spin precessions per revolution (with respect to the momentum vector) is given by the spin tune $\nu_s = G\gamma$
  - *„Frozen Spin“*-Technique requires $\vec{\Omega}_{\mathrm{MDM}} = 0$
    - Not applicable

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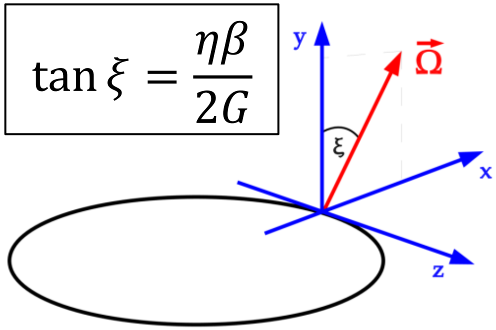
Measurement Principle @ COSY

- Static storage ring:
  - Tilt of $\vec{\Omega}$ in main dipoles due to EDM contribution

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

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

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



$$\boxed{\tan\xi = \frac{\eta\beta}{2G}}$$

- $\vec{\Omega}_{MDM}$ vertical, $\vec{\Omega}_{EDM}$ radial
- Small tilt of spin precession axis.
- Vertical oscillation is too small to measure, if $|\vec{\Omega}_{EDM}| \ll |\vec{\Omega}_{MDM}|$

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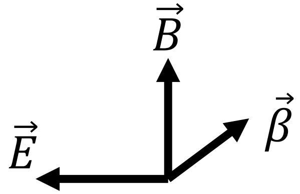
Measurement Principle @ COSY

- Idea:
  - Radiofrequent field oscillating with spin precession frequency
  - Pure electric field: coherent betatron oscillations
  - Minimization using Wien filter configuration
    - RF-E×B-Dipole

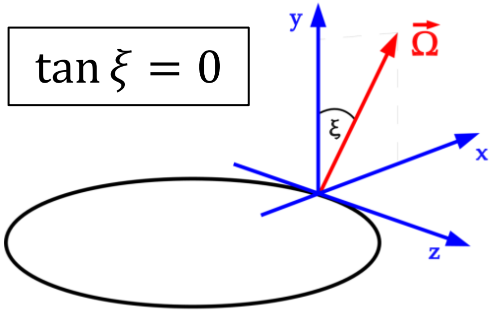
$$\vec{\Omega}_{\mathrm{MDM}} = \frac{e}{\gamma m}\left[G\gamma\,\vec{B} - \left(G - \frac{1}{\gamma^2-1}\right)\frac{\vec{E}\times\vec{\beta}}{c} - \frac{G\gamma^2}{\gamma+1}\,\vec{\beta}(\vec{\beta}\cdot\vec{B})\right]$$

$$\vec{\Omega}_{\mathrm{EDM}} = \frac{e}{m}\frac{\eta}{2}\left[\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B} - \frac{\gamma}{\gamma+1}\,\vec{\beta}\left(\vec{\beta}\cdot\frac{\vec{E}}{c}\right)\right] = \vec{0}$$



- Device is EDM transparent, no tilt ξ like in guiding dipoles
  - Slowly oscillating signal

$$\boxed{\tan\xi = 0}$$



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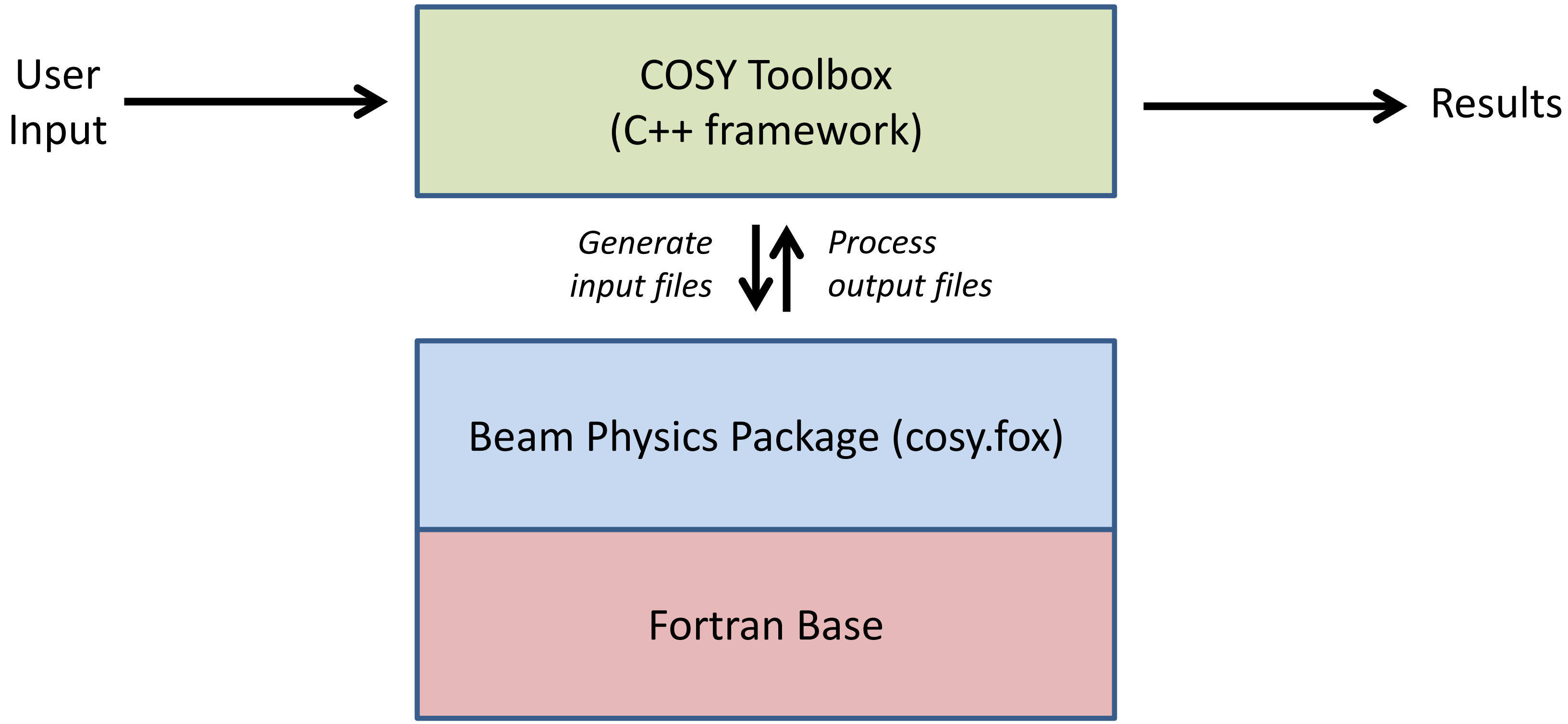
Simulation framework

- New package on top of COSY Infinity



User Input

COSY Toolbox
(C++ framework)

Results

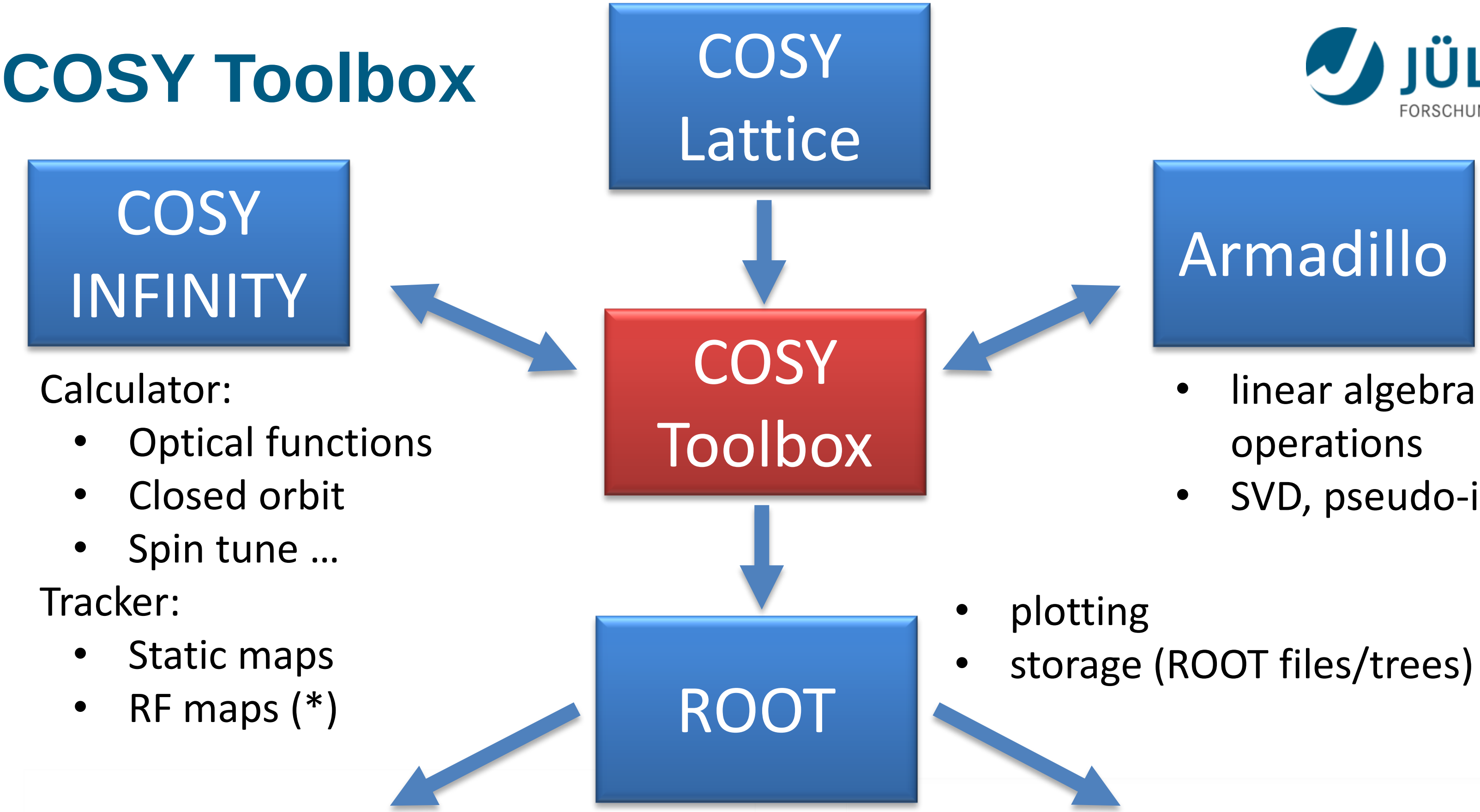
Generate input files

Process output files

Beam Physics Package (cosy.fox)

Fortran Base

COSY Toolbox



COSY Lattice

COSY INFINITY

- Calculator:
  - Optical functions
  - Closed orbit
  - Spin tune …
- Tracker:
  - Static maps
  - RF maps (*)

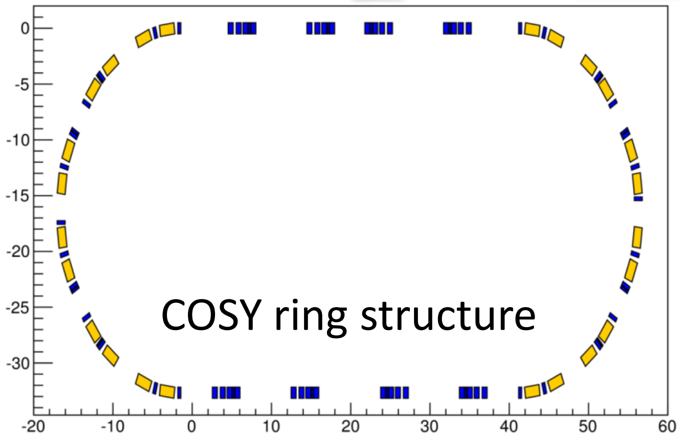
COSY Toolbox

Armadillo

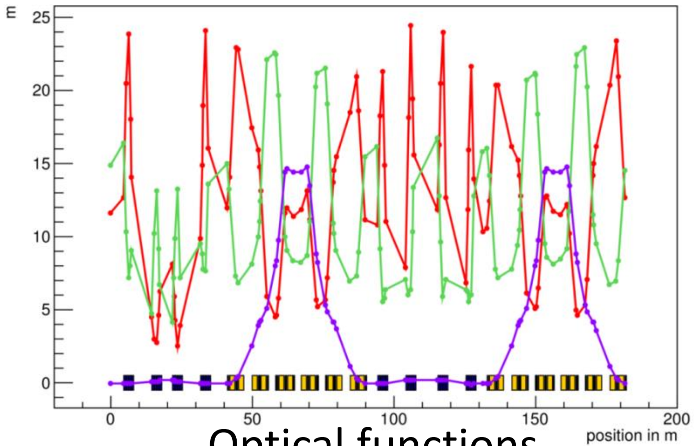
- linear algebra operations
- SVD, pseudo-inverse

ROOT

- plotting
- storage (ROOT files/trees)



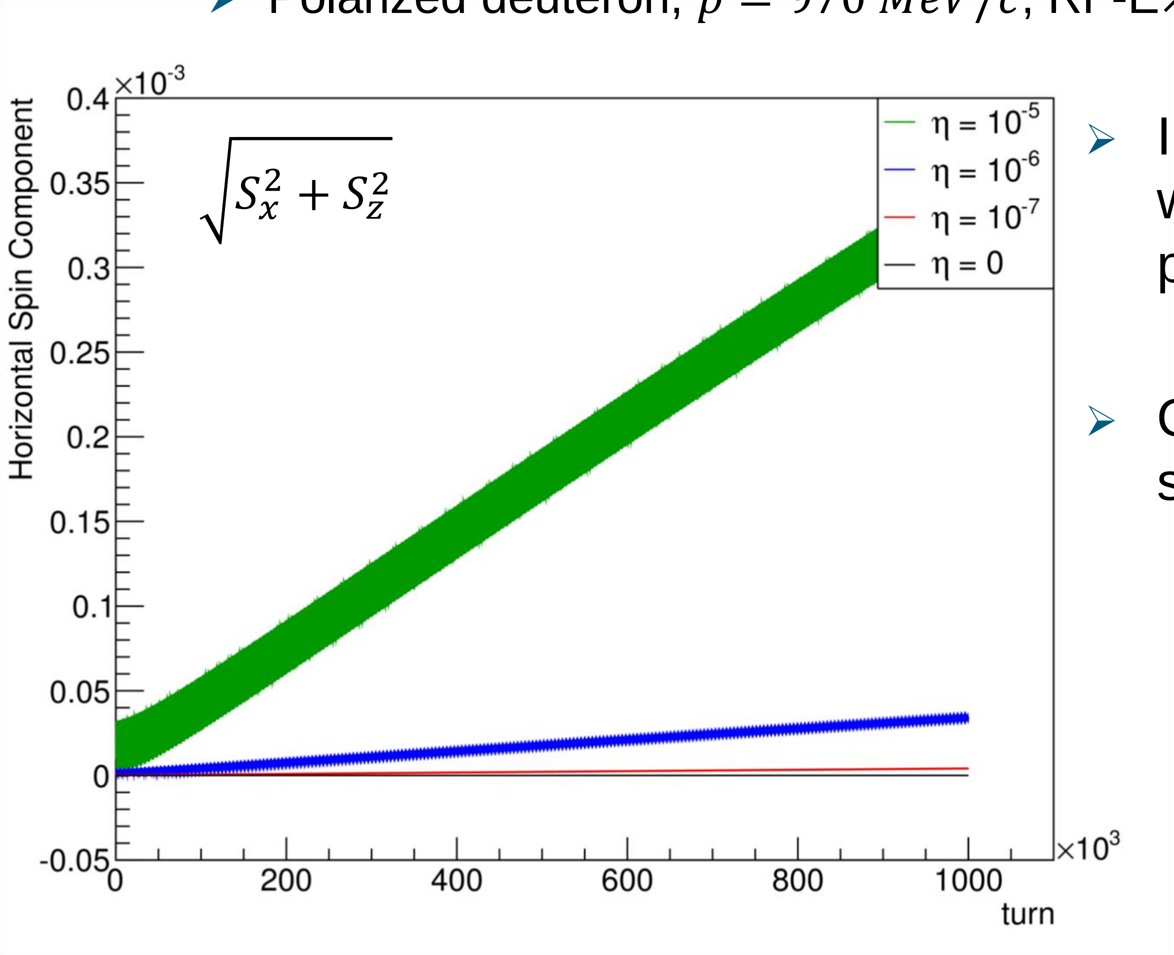
COSY ring structure



Optical functions

Measurement Principle @ COSY

- RF-Simulation for ideal ring shows effect
  - Polarized deuteron, $p = 970\ MeV/c$, RF-E×B-Dipole strength: 0.3 mT



- Initial vertical polarization will precess into horizontal plane, if $\eta \neq 0$
- Oscillation of horizontal spin component:

$$\sin(\theta \cdot n) \approx \theta \cdot n$$

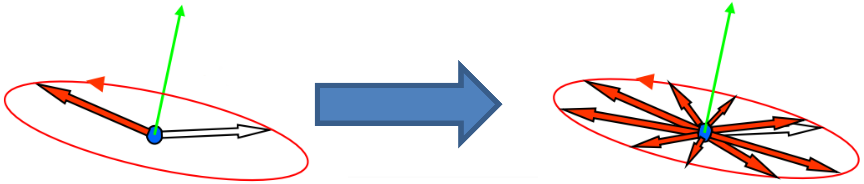
$$\theta \approx \frac{\psi\xi}{2}$$

ψ: max. spin rotation in RF field

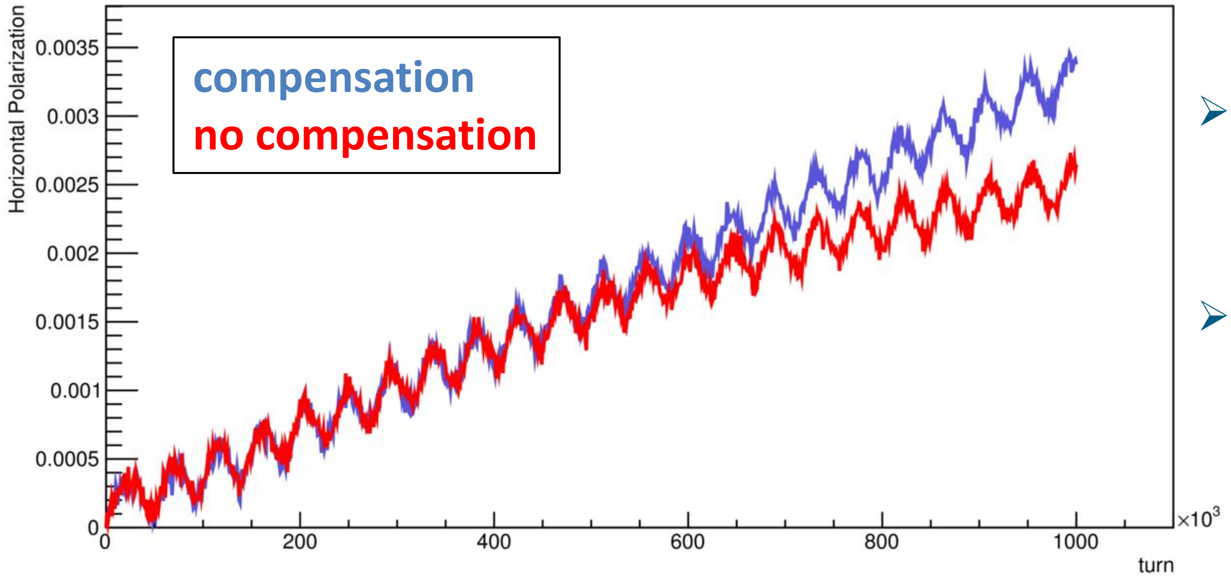
ξ: EDM tilt

Spin Coherence Time

- Spin precession in ideal magnetic ring around vertical axis:
  - Spin tune: $\nu_s = G\gamma$
  - Energy deviations lead to different precession speed



Horizontal polarization vanishes!



- Buildup limited by Spin Coherence Time
- Decoherence needs to be minimized

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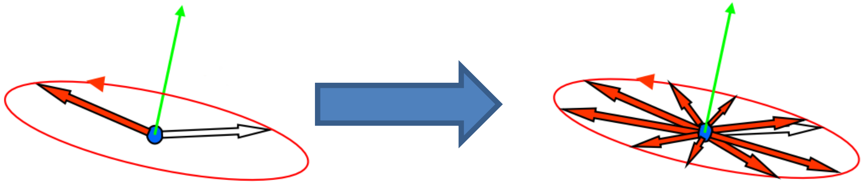
Spin Coherence Time

- Spin precession in ideal magnetic ring around vertical axis:
  - Spin tune: $\nu_s = G\gamma$
  - Energy deviations lead to different precession speed



Horizontal polarization vanishes!

- Consider relative change of revolution time of single particle:
  - $\frac{\Delta T}{T_0} = \frac{\Delta L}{L_0} - \frac{\Delta\beta}{\beta_0} - \frac{\Delta L}{L_0}\frac{\Delta\beta}{\beta_0} + \left(\frac{\Delta\beta}{\beta_0}\right)^2$ with $T_0 = \frac{L_0}{\beta_0 c}$

- No coupling:
  - $\frac{\Delta L}{L_0} = \left(\frac{\Delta L}{L_0}\right)_x + \left(\frac{\Delta L}{L_0}\right)_y + \left(\frac{\Delta L}{L_0}\right)_{\frac{\Delta p}{p}}$
  - $\left(\frac{\Delta L}{L_0}\right)_{\frac{\Delta p}{p}} = \alpha_0 \cdot \frac{\Delta p}{p} + \alpha_1 \cdot \left(\frac{\Delta p}{p}\right)^2$

Spin Coherence Time II

- $$\left\langle \frac{\Delta T}{T_0}\right\rangle = \left(\alpha_0 - \frac{1}{\gamma_0^2}\right)\left\langle\frac{\Delta p}{p}\right\rangle + \left(\alpha_1 + \frac{3}{2}\frac{\beta_0^2}{\gamma_0^2} - \frac{\alpha_0}{\gamma_0^2} + \frac{1}{\gamma_0^4}\right)\left\langle\left(\frac{\Delta p}{p}\right)^2\right\rangle + \left\langle\left(\frac{\Delta L}{L_0}\right)_x\right\rangle + \left\langle\left(\frac{\Delta L}{L_0}\right)_y\right\rangle = 0$$

$\uparrow$ bunched

- Canceling energy deviations ($\nu_s = G\gamma$): $\left\langle\frac{\Delta\gamma}{\gamma_0}\right\rangle = 0$
  - $$\frac{\Delta p}{p} \approx \frac{1}{\beta_0^2}\frac{\Delta\gamma}{\gamma_0} - \frac{1}{2\beta_0^4\gamma_0^2}\left(\frac{\Delta\gamma}{\gamma}\right)^2$$

- Three conditions for $\left\langle\frac{\Delta\gamma}{\gamma_0}\right\rangle = 0$:
  - $$\left\langle\left(\frac{\Delta L}{L_0}\right)_u\right\rangle = -\frac{\pi}{L_0}\cdot\epsilon_u\cdot\boldsymbol{\xi_u} = 0, \quad u \in \{x, y\}$$
  - $$\boldsymbol{\Delta} \equiv \left[\boldsymbol{\alpha_1} + \frac{3}{2\gamma_0^2}\left(\beta_0^2 - \left(\alpha_0 - \frac{1}{\gamma_0^2}\right)\right)\right] = 0$$

$$\epsilon_u = \frac{u_{max}^2}{\beta_u}$$

$$\xi_u = \frac{\Delta Q_u/Q_u}{\Delta p/p}$$

- Magnetic sextupoles are an effective tool to maintain these conditions.

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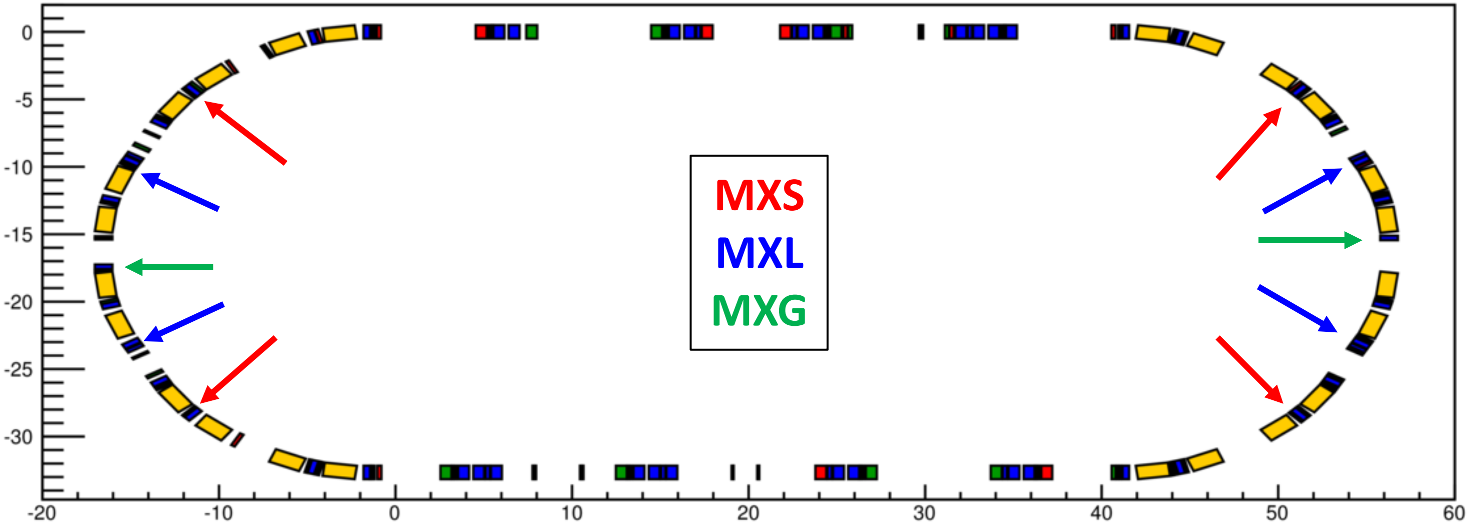
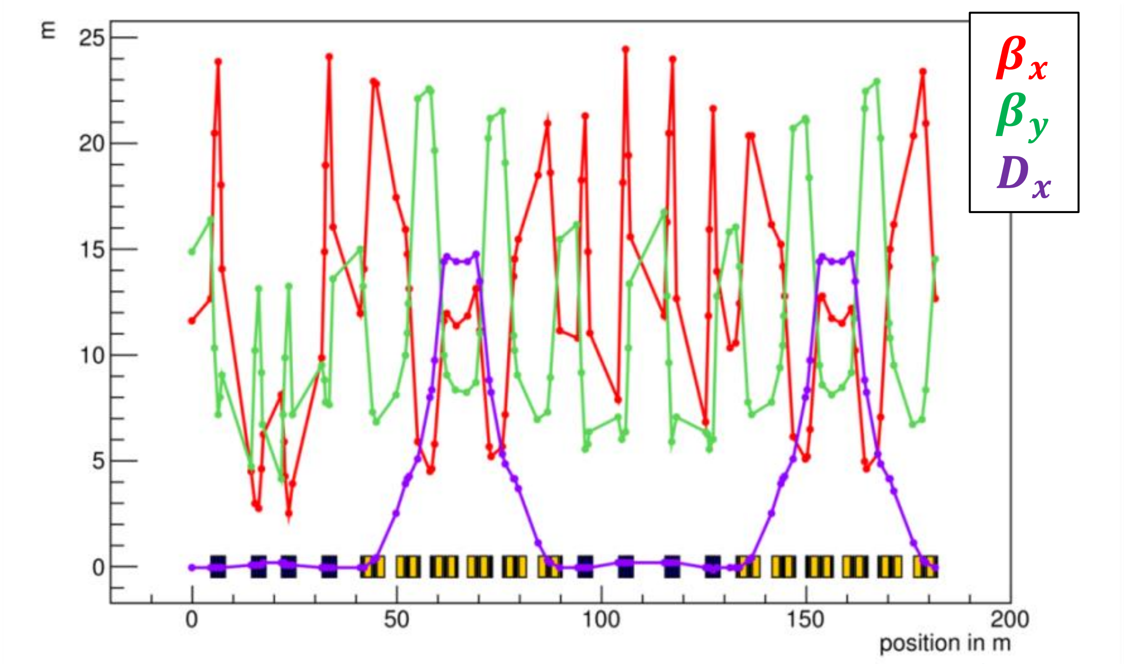
Sextupoles at COSY





- Straights:
  - Minimized dispersion
- Arcs:
  - Large dispersion
  - 3 sextupole families

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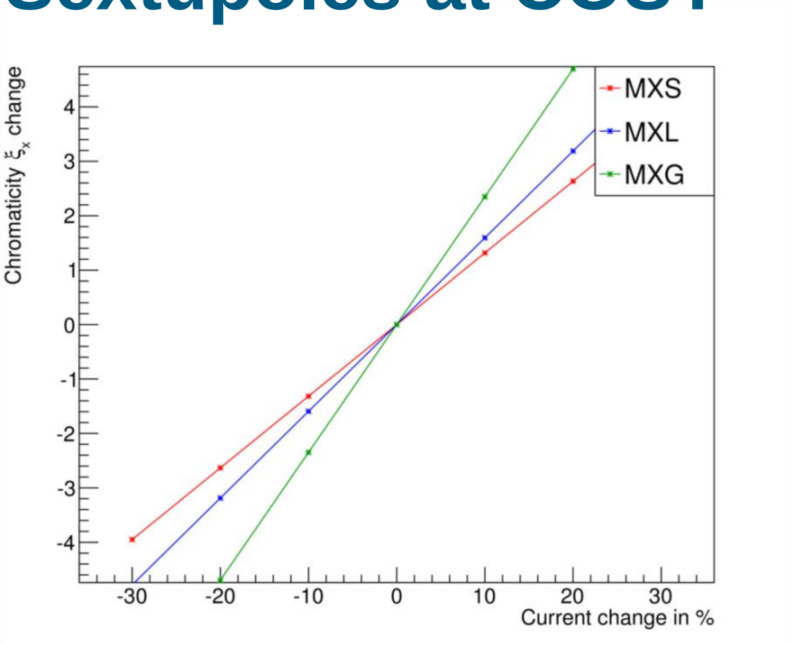
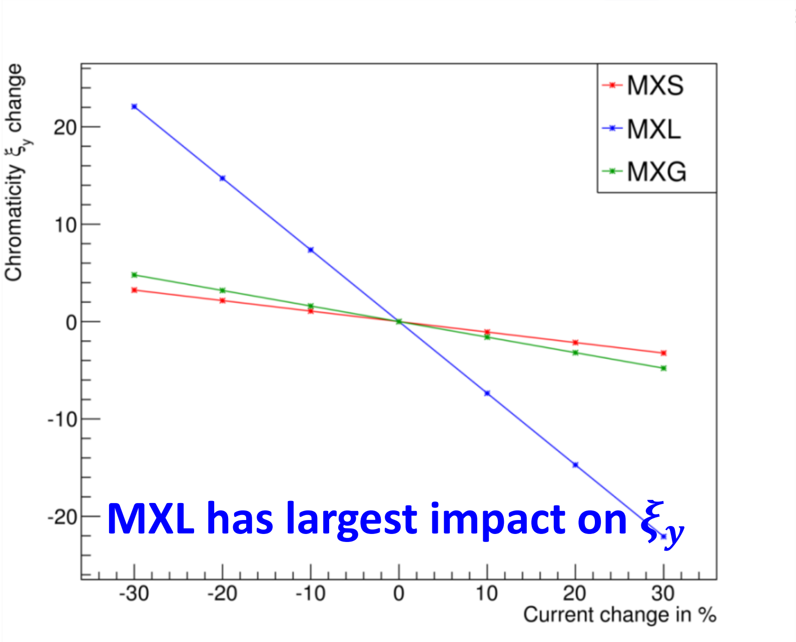
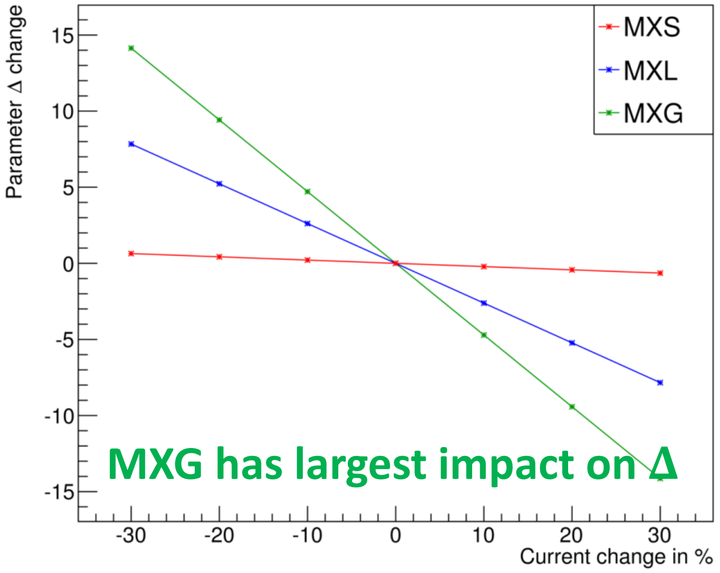
Sextupoles at COSY





MXL has largest impact on ξ_y



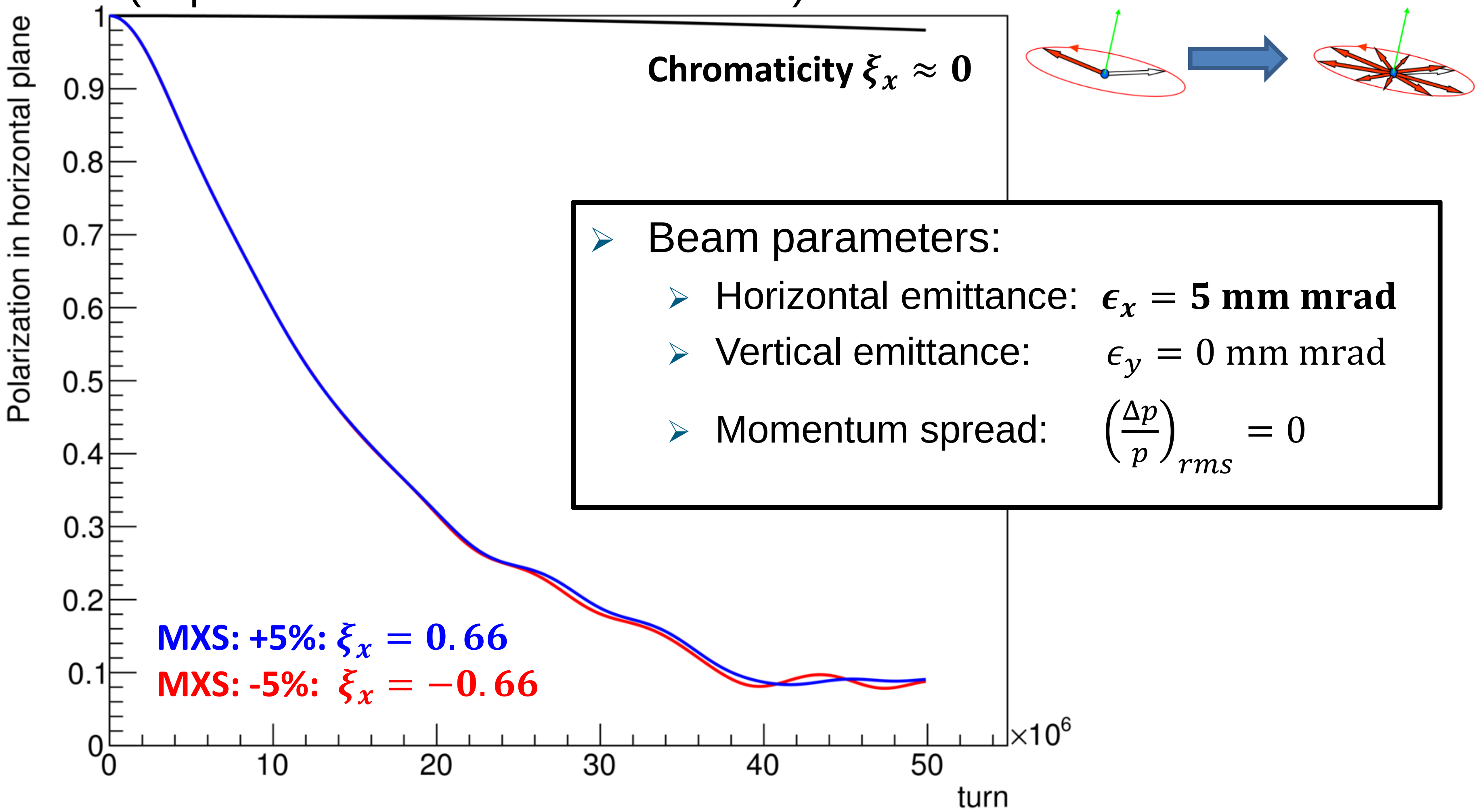
MXG has largest impact on Δ

- Linear equation system to minimize ξ_x, ξ_y and Δ at the same time

- MXL dominates ξ_y change
- MXG dominates Δ change

SCT Simulations

- Deuterons, $p = 970\ MeV/c$, initially radial polarized
  (→ precession around vertical axis)



Chromaticity $\xi_x \approx 0$

MXS: +5%: $\xi_x = 0.66$

MXS: -5%: $\xi_x = -0.66$

- Beam parameters:
  - Horizontal emittance: $\boldsymbol{\epsilon_x = 5\ \mathrm{mm\ mrad}}$
  - Vertical emittance: $\epsilon_y = 0\ \mathrm{mm\ mrad}$
  - Momentum spread: $\left(\frac{\Delta p}{p}\right)_{rms} = 0$

SCT Simulations

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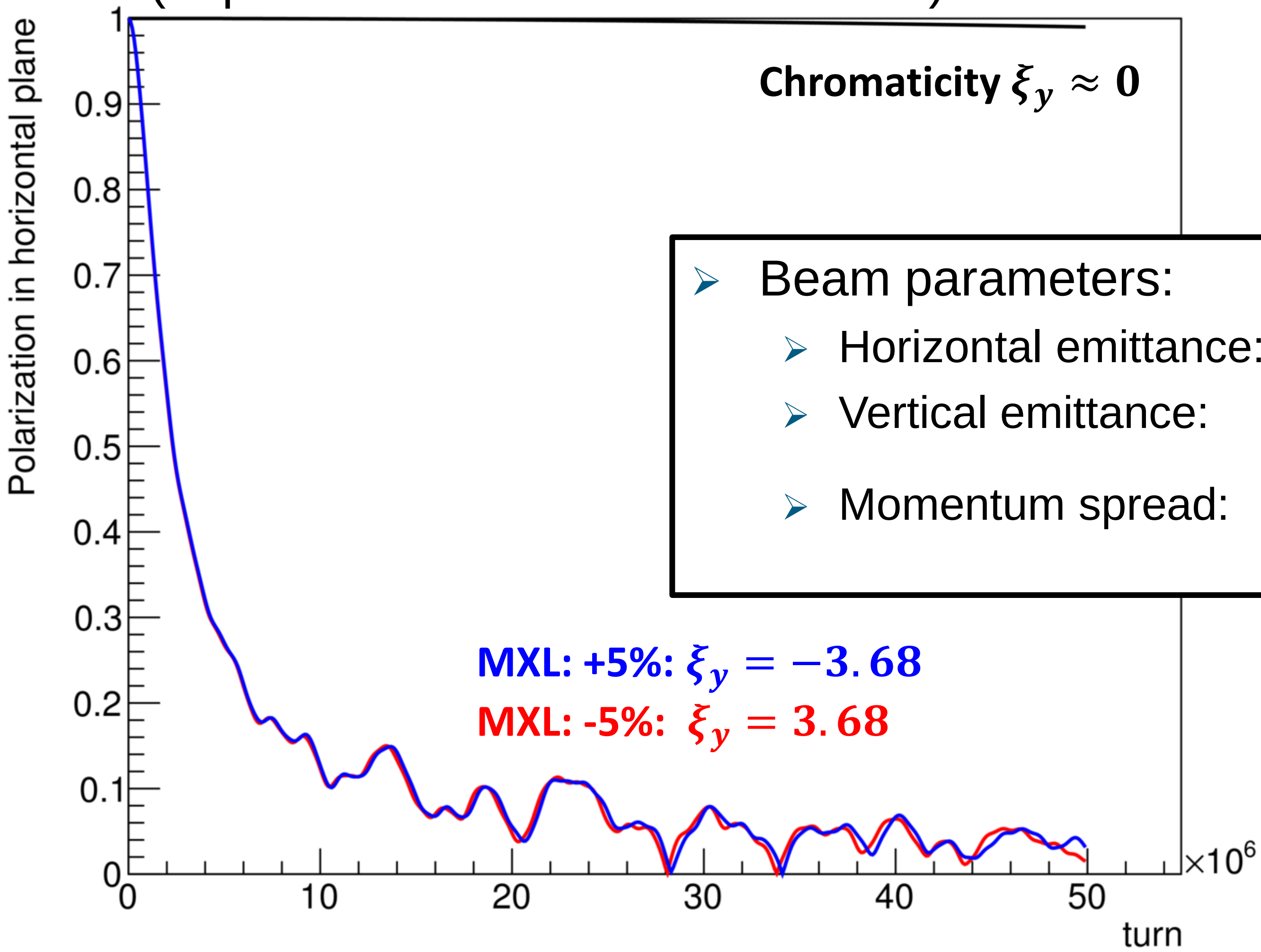

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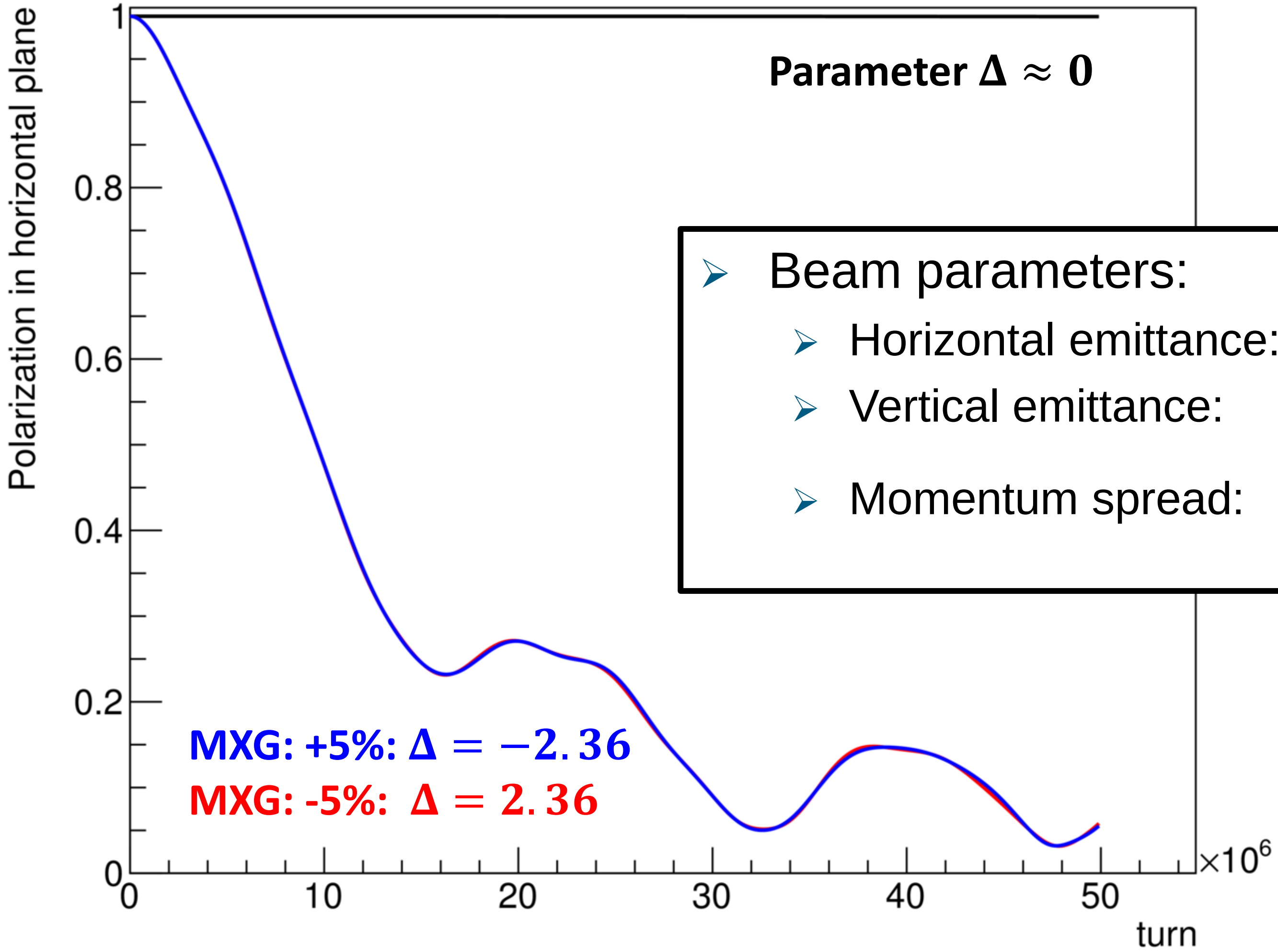

Parameter $\boldsymbol{\Delta \approx 0}$

MXG: +5%: $\boldsymbol{\Delta = -2.36}$

MXG: -5%: $\boldsymbol{\Delta = 2.36}$

- Beam parameters:
  - Horizontal emittance: $\epsilon_x = 0\ \mathrm{mm\ mrad}$
  - Vertical emittance: $\epsilon_y = 0\ \mathrm{mm\ mrad}$
  - Momentum spread: $\left(\frac{\Delta p}{p}\right)_{rms} = 5 \cdot 10^{-4}$

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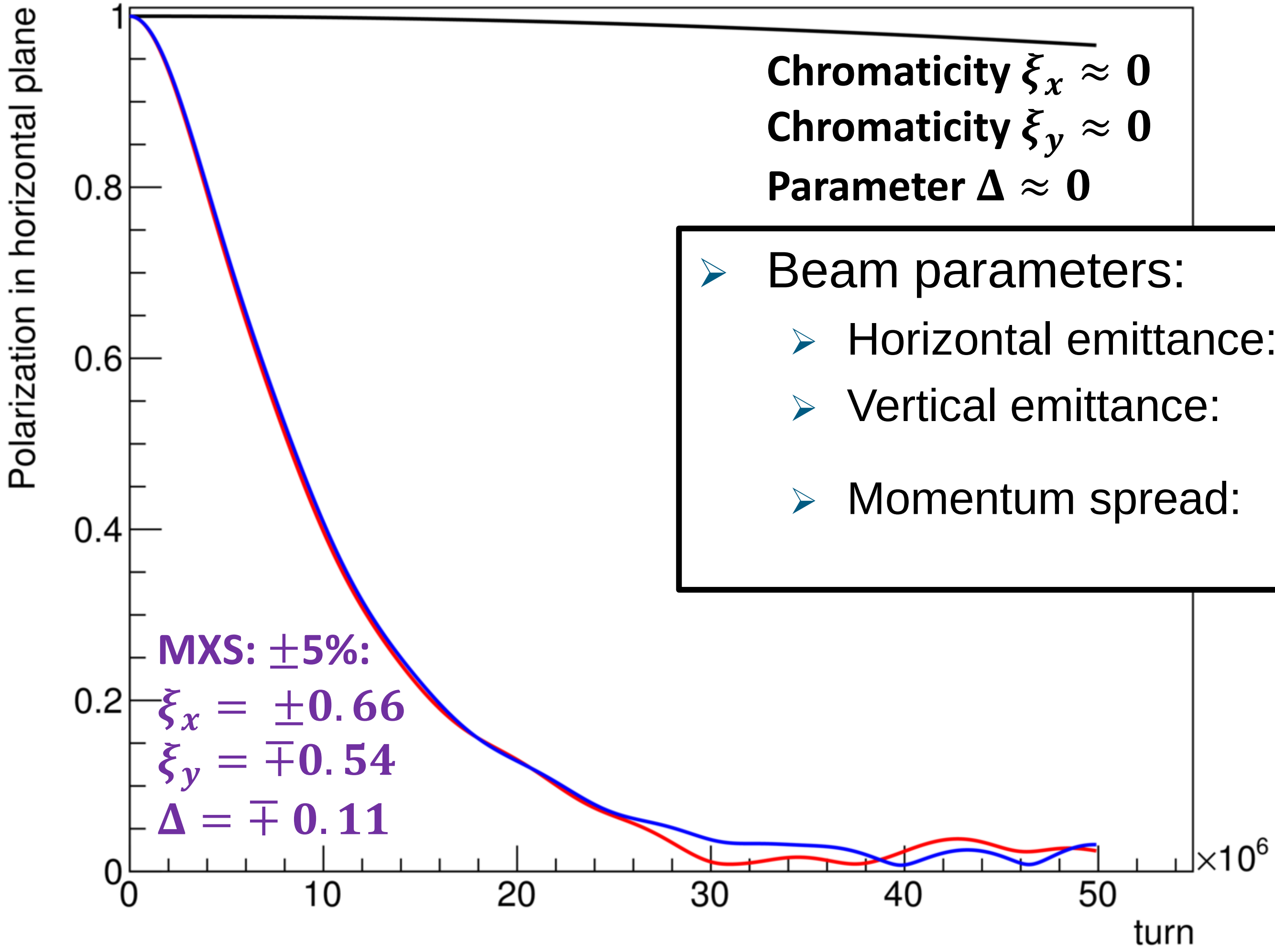
SCT Simulations

- Deuterons, $p = 970\ MeV/c$, initially radial polarized (→ precession around vertical axis)



Chromaticity $\xi_x \approx 0$
Chromaticity $\xi_y \approx 0$
Parameter $\Delta \approx 0$

MXS: ±5%:
$\xi_x = \pm 0.66$
$\xi_y = \mp 0.54$
$\Delta = \mp 0.11$

- Beam parameters:
  - Horizontal emittance: $\epsilon_x = 5\ \mathrm{mm\ mrad}$
  - Vertical emittance: $\epsilon_y = 5\ \mathrm{mm\ mrad}$
  - Momentum spread: $\left(\frac{\Delta p}{p}\right)_{rms} = 5 \cdot 10^{-4}$

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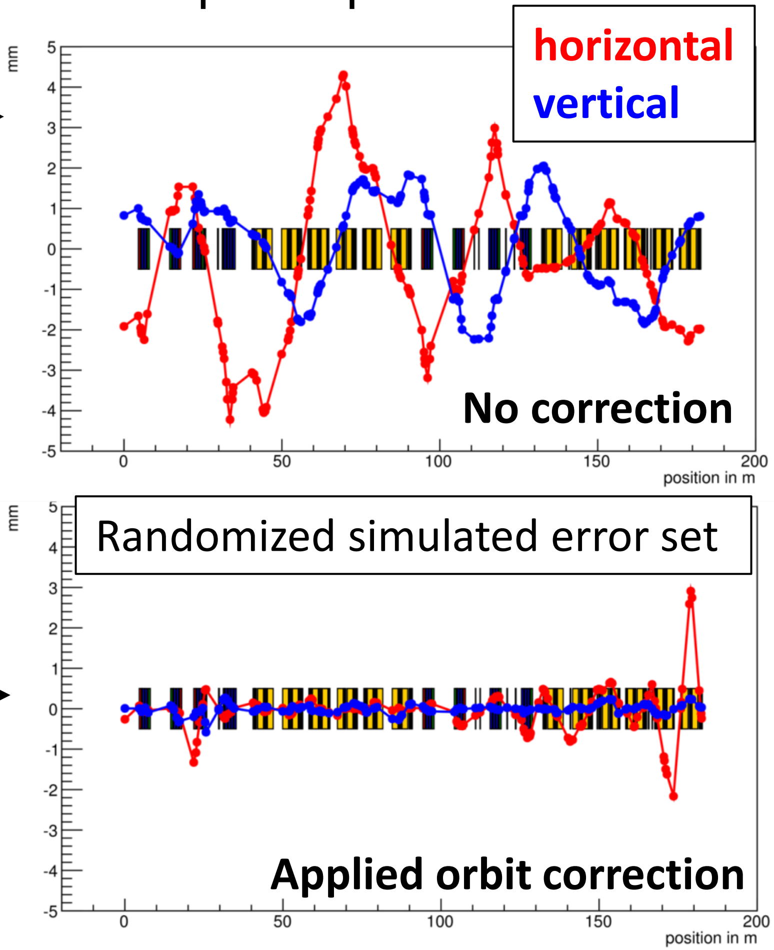
Misalignments

- Up to now only the ideal ring was considered.
- Misalignments and field errors of dipoles and quadrupoles introduce additional field components.
  - Beam orbit displacement
  - Spin rotations
- COSY main magnets:
  - 24 dipoles
  - 56 quadrupoles
- Orbit diagnosis & correction:
  - ~60 beam position monitors
  - ~40 correctors



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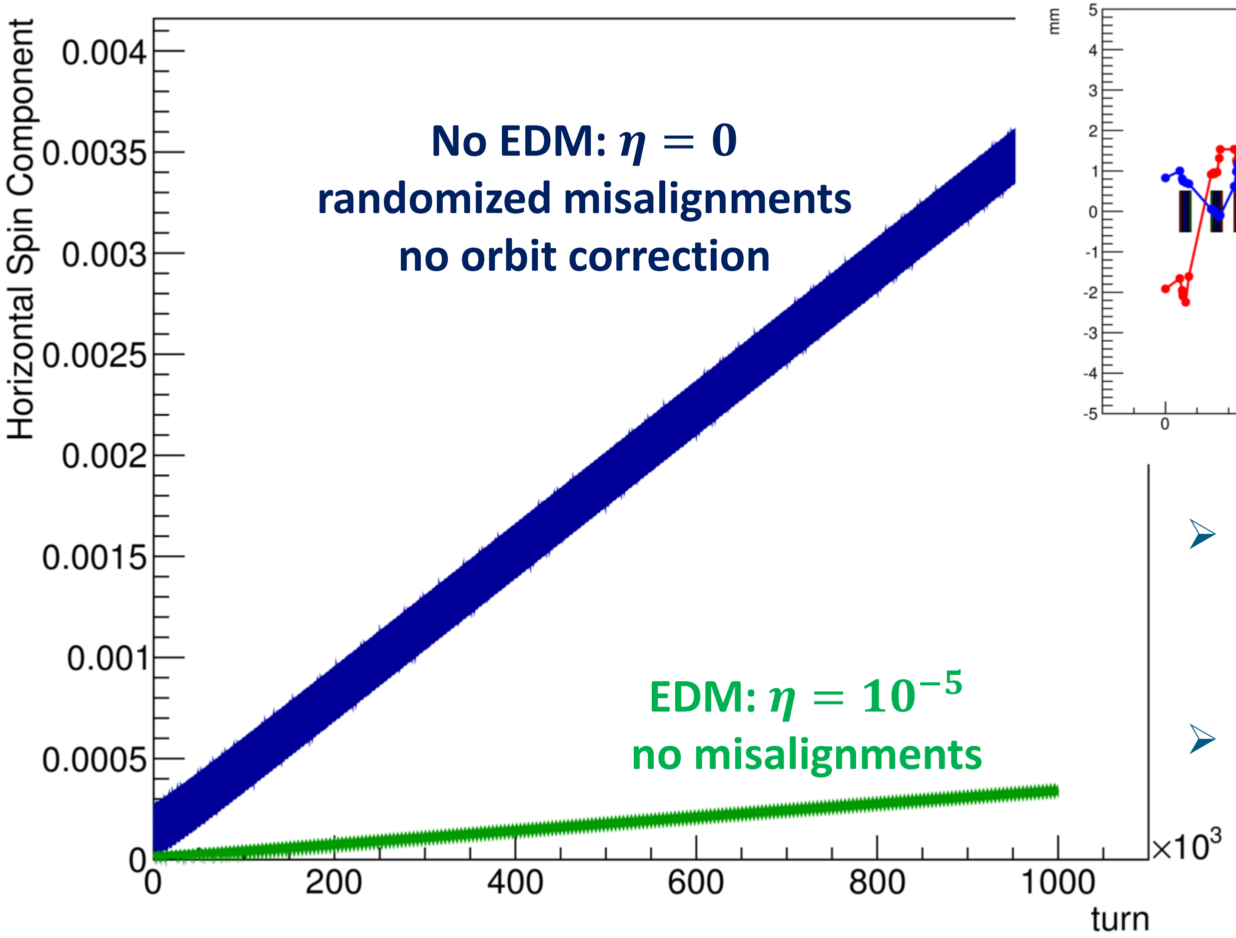
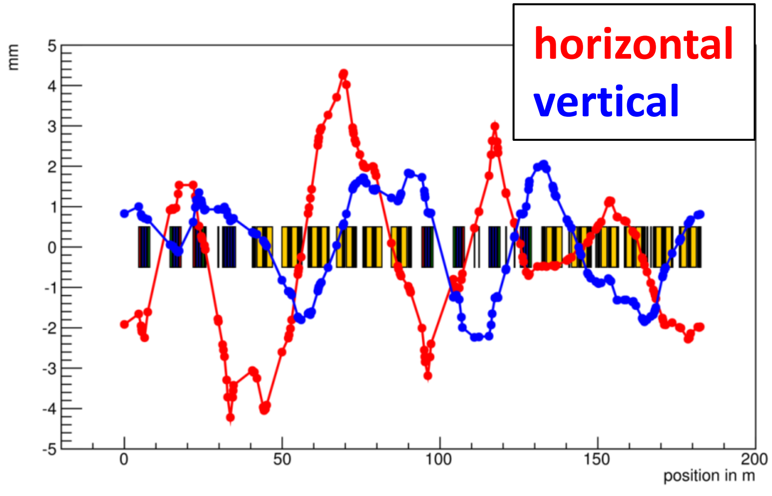
False “EDM signal“

RF-E×B-Dipole strength: 0.3 mT

- No EDM, but misalignments.
  What will happen to the polarization?





- Large contribution due to uncorrected misalignments
- Apply corrections to minimize

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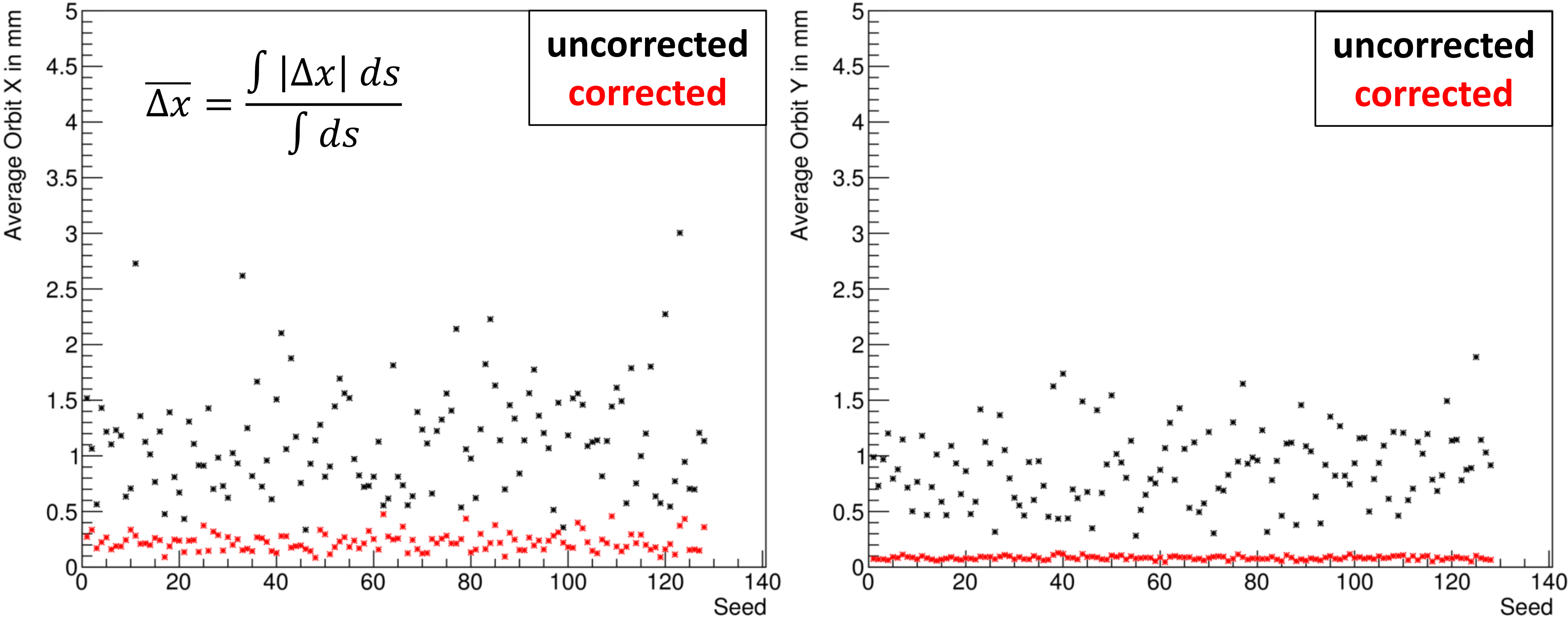
Simulations of Misalignments

- Randomize different sets of misalignments and field errors.
- Shifts of elements in all three directions with $\boldsymbol{\sigma = 10^{-4}\ m}$
- Rotations of elements around all three axes with $\boldsymbol{\sigma = 10^{-4}\ rad}$
- Relative magnetic field error of main dipoles with $\boldsymbol{\sigma = 10^{-4}}$



$$\overline{\Delta x} = \frac{\int |\Delta x|\, ds}{\int ds}$$

Simulations of Misalignments

- Randomize different sets of misalignments and field errors.
- Shifts of elements in all three directions with $\boldsymbol{\sigma = 10^{-4}\ m}$
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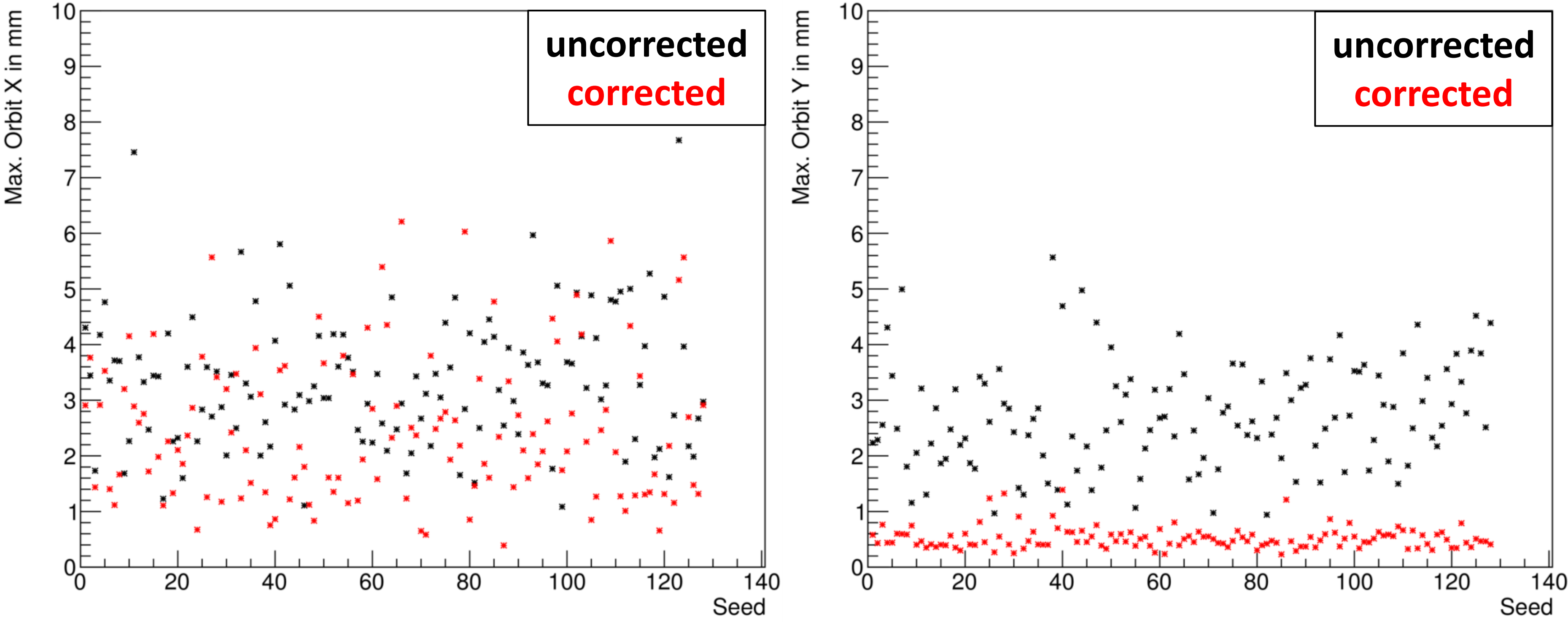
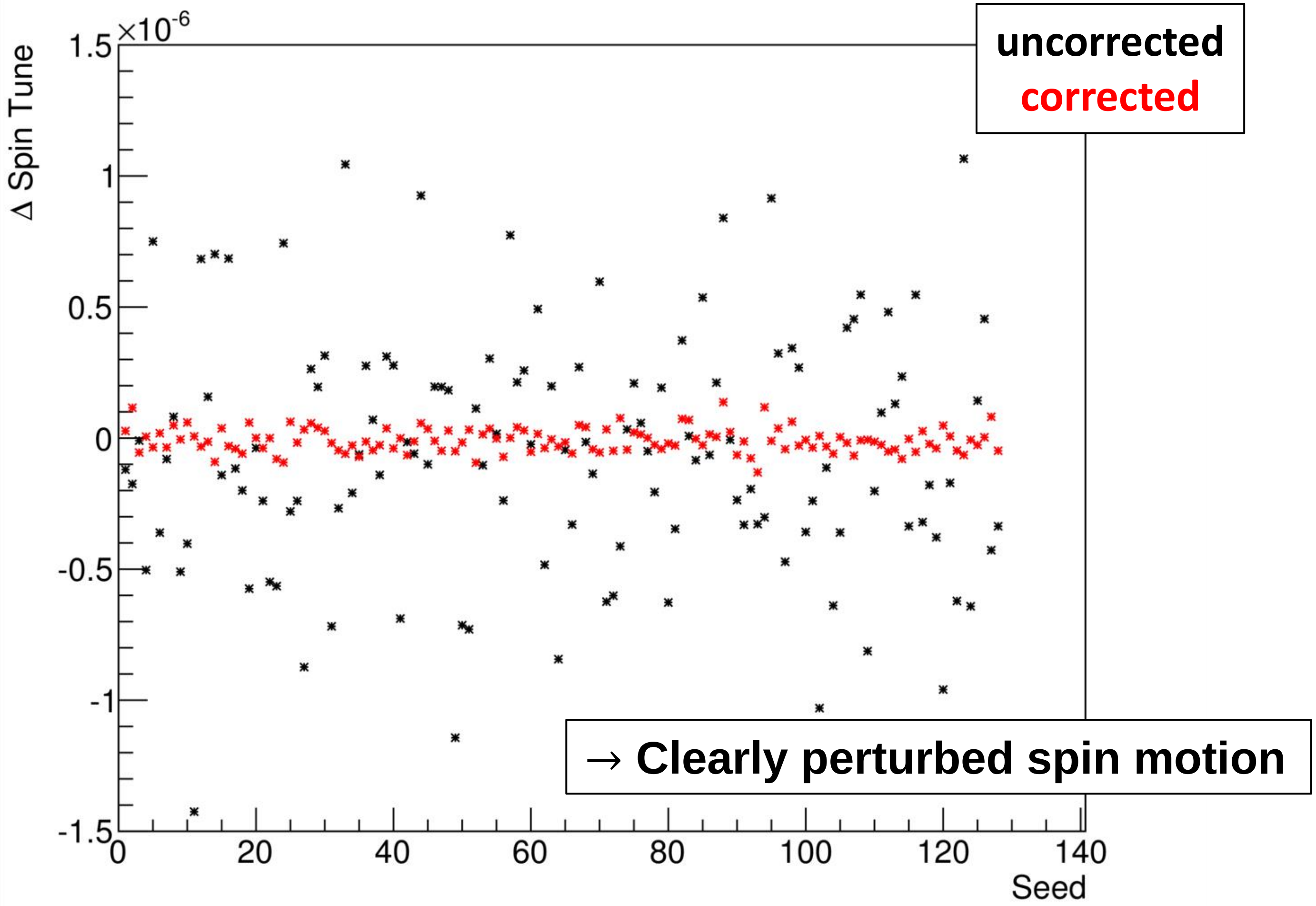


Influence on Spin Tune

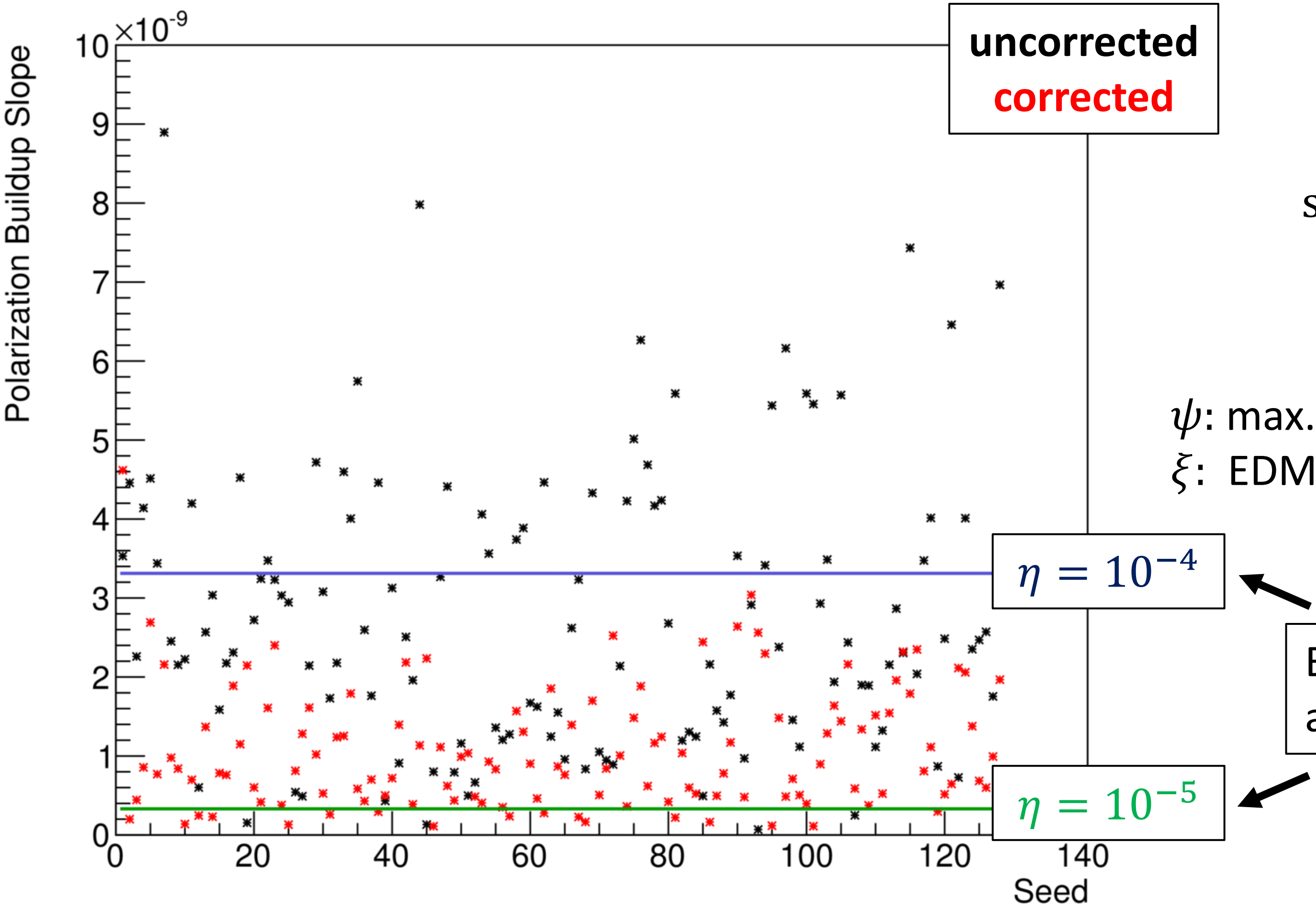
- Non commutative spin rotations change the spin tune $\nu_s = G\gamma$
- Local orbit corrections partially compensate this effect



→ Clearly perturbed spin motion

Horizontal Polarization Buildup

- Polarization buildup caused by misalignments is in the order of an EDM: $\eta \sim 10^{-4} \rightarrow d \sim 5.3 \cdot 10^{-19}$ e cm



$$\sin(\theta \cdot n) \approx \theta \cdot n$$

$$\theta \approx \frac{\psi\xi}{2}$$

ψ: max. spin rotation in RF field
ξ: EDM tilt

Buildup in case of EDM and no misalignments

Summary & Outlook

- EDM measurements in storage rings require a long polarization lifetime in vertical direction as well as in the horizontal plane.

- Chromaticies ξ_x, ξ_y and $\Delta \equiv \left[\alpha_1 + \frac{3}{2\gamma_0^2}\left(\beta_0^2 - \left(\alpha_0 - \frac{1}{\gamma_0^2}\right)\right)\right]$ are crucial parameters for minimization of energy spread inside a bunched beam.

- Large set of measured horizontal depolarization for various sextupole configurations has to be understood using tracking simulations.

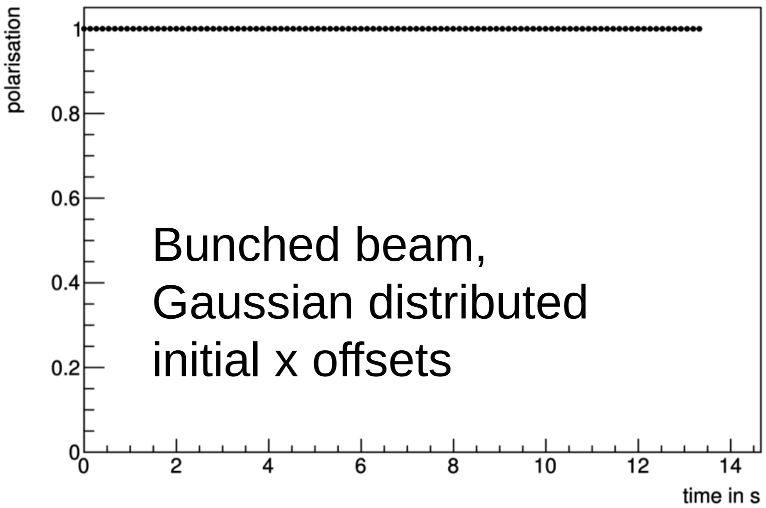
- Misalignments create false EDM signal in resonant buildup method. Method of local orbit corrections needs to be studied to minimize this signal, while not compensating the EDM effect itself.

SPARES

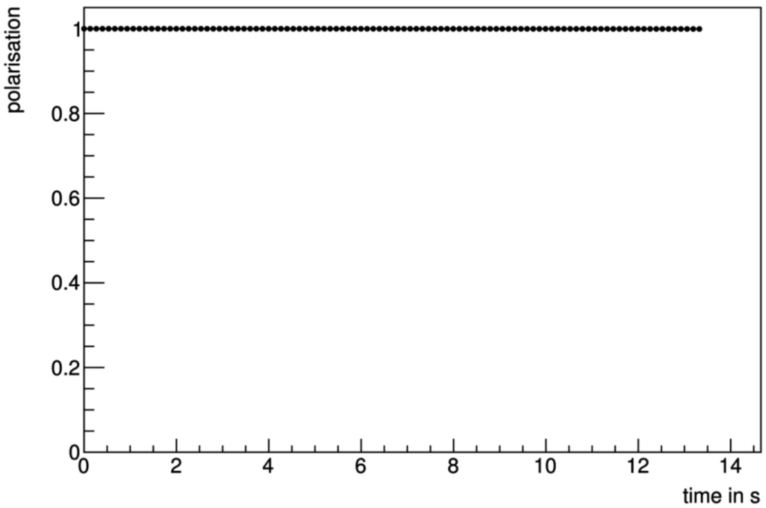
Path-lengthening (horizontal)

- Several settings leading to vanishing path-lengthening:

#	MXS / m^{-3}	MXL / m^{-3}	MXG / m^{-3}
1	-0.002 (0)	-0.506	0.775
2	0.999 (1)	-0.522	0.497
3	2.001 (2)	-0.538	0.218
4	3.002 (3)	-0.554	-0.061
5	4.004 (4)	-0.570	-0.340



Bunched beam,
Gaussian distributed
initial x offsets



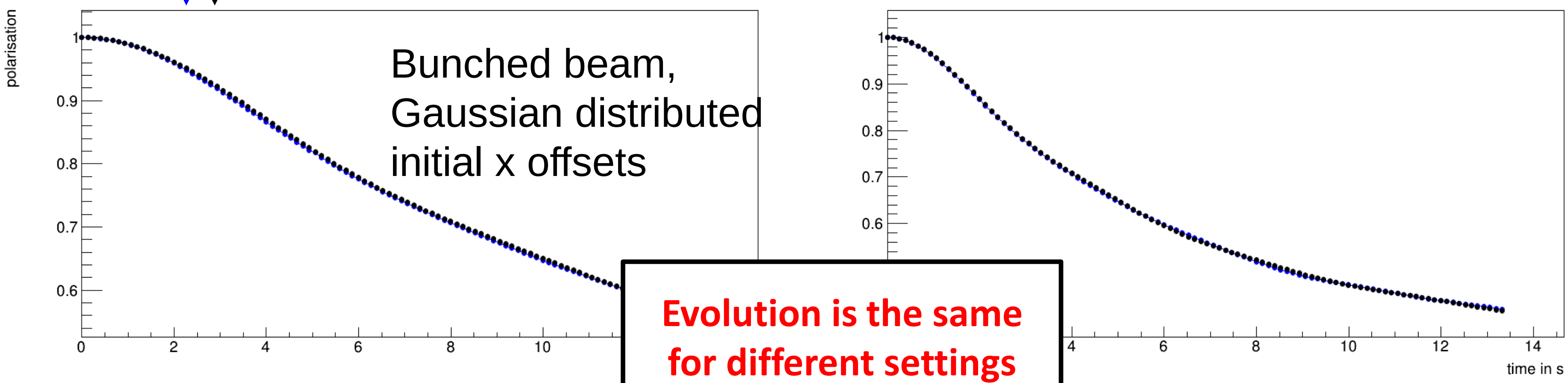
Path-lengthening (horizontal)

- Deviations from path-lengthening cancellation:

#	MXS / m^{-3}	MXL / m^{-3}	MXG / m^{-3}
1	-0.002 (0)	-0.506	0.775
2	0.999 (1)	-0.522	0.497
3	2.001 (2)	-0.538	0.218
4	3.002 (3)	-0.554	-0.061
5	4.004 (4)	-0.570	-0.340

MXS: +1

MXS: +2



Bunched beam, Gaussian distributed initial x offsets

Evolution is the same for different settings

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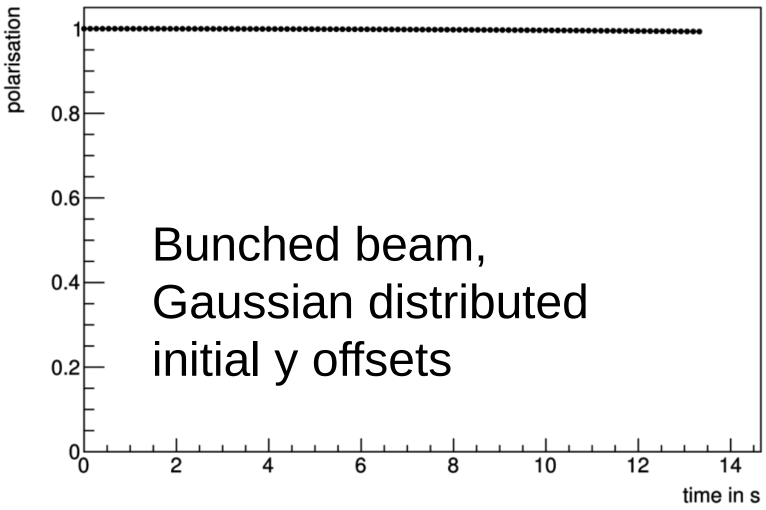
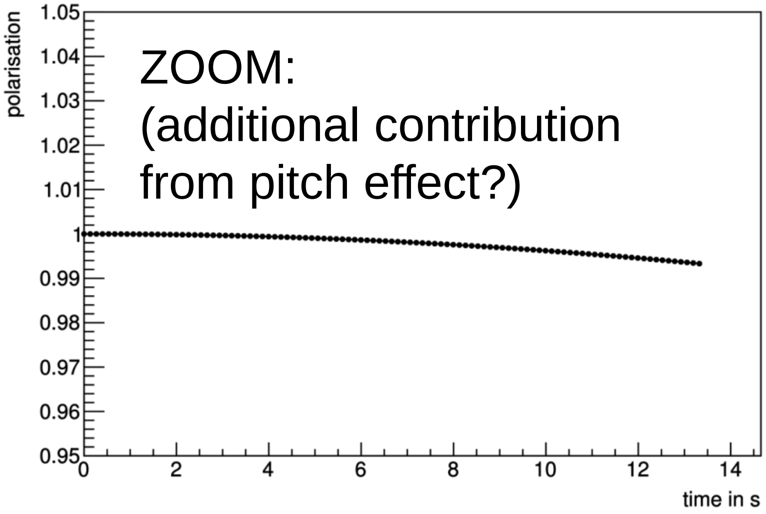
Path-lengthening (vertical)

- Several settings leading to vanishing path-lengthening:

#	MXS / m^{-3}	MXL / m^{-3}	MXG / m^{-3}
1	0	-0.506 (-0.506)	0.775
2	1	-0.522 (-0.522)	0.497
3	2	-0.538 (-0.538)	0.218
4	3	-0.554 (-0.554)	-0.061
5	4	-0.570 (-0.570)	-0.340



Bunched beam,
Gaussian distributed
initial y offsets



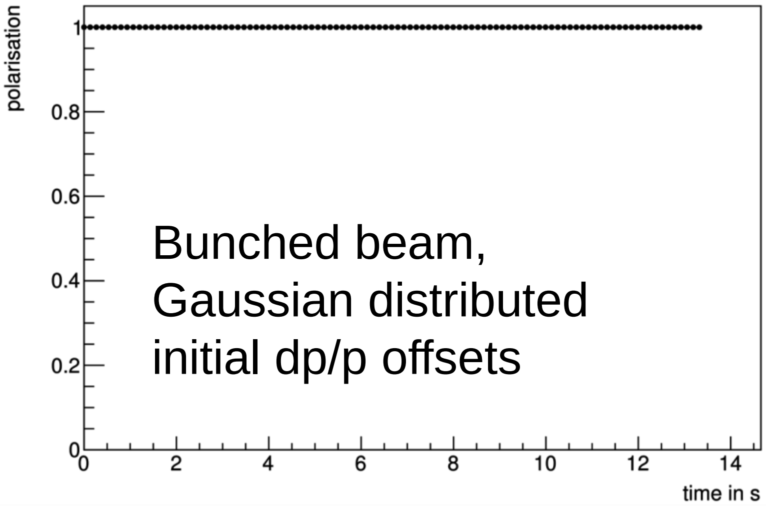
ZOOM:
(additional contribution
from pitch effect?)

Path-lengthening (longitudinal)

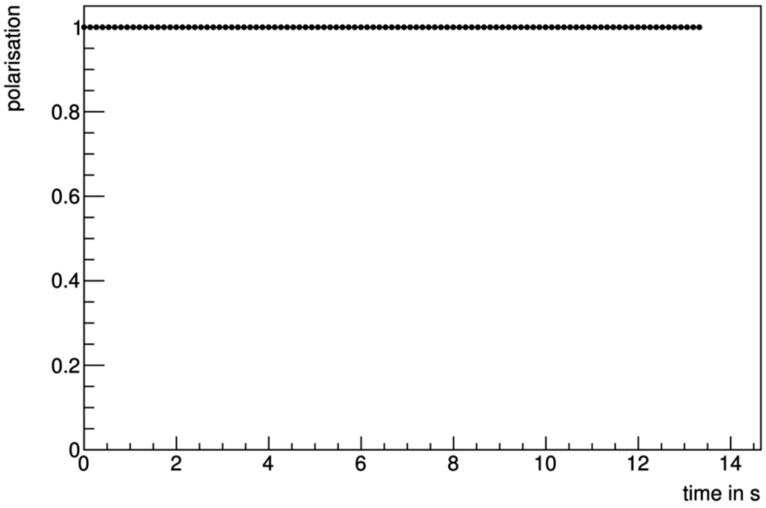
- Several settings to fulfill the condition:

$$\left[\alpha_1 + \frac{3}{2\gamma_0^2}\left(\beta_0^2 - \left(\alpha_0 - \frac{1}{\gamma_0^2}\right)\right)\right] = 0$$

#	MXS / m^{-3}	MXL / m^{-3}	MXG / m^{-3}
1	2	2	-0.284
2	-2	-2	0.825



Bunched beam, Gaussian distributed initial dp/p offsets



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COSY Toolbox

COSY Lattice

COSY Toolbox

COSY INFINITY

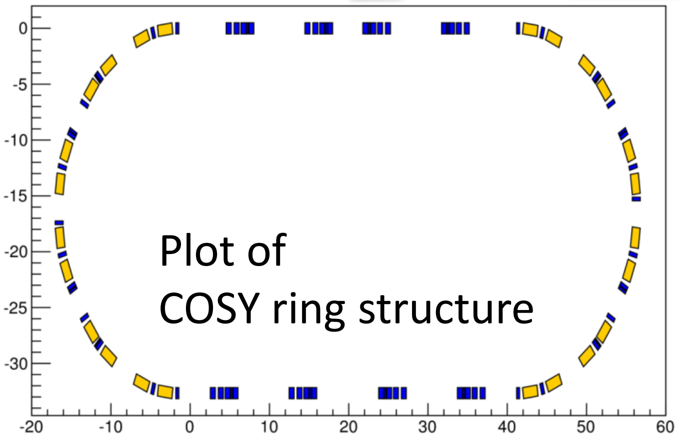
- Calculator:
  - Optical functions
  - Orbit
  - Spintune …
- Tracker:
  - Static maps
  - RF maps (*)

Armadillo

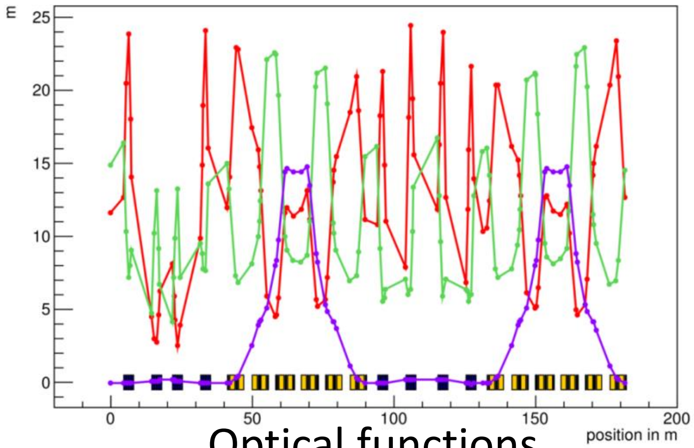
- linear algebra operations
- SVD, pseudo-inverse

ROOT

- plotting
- storage (ROOT files/Trees)



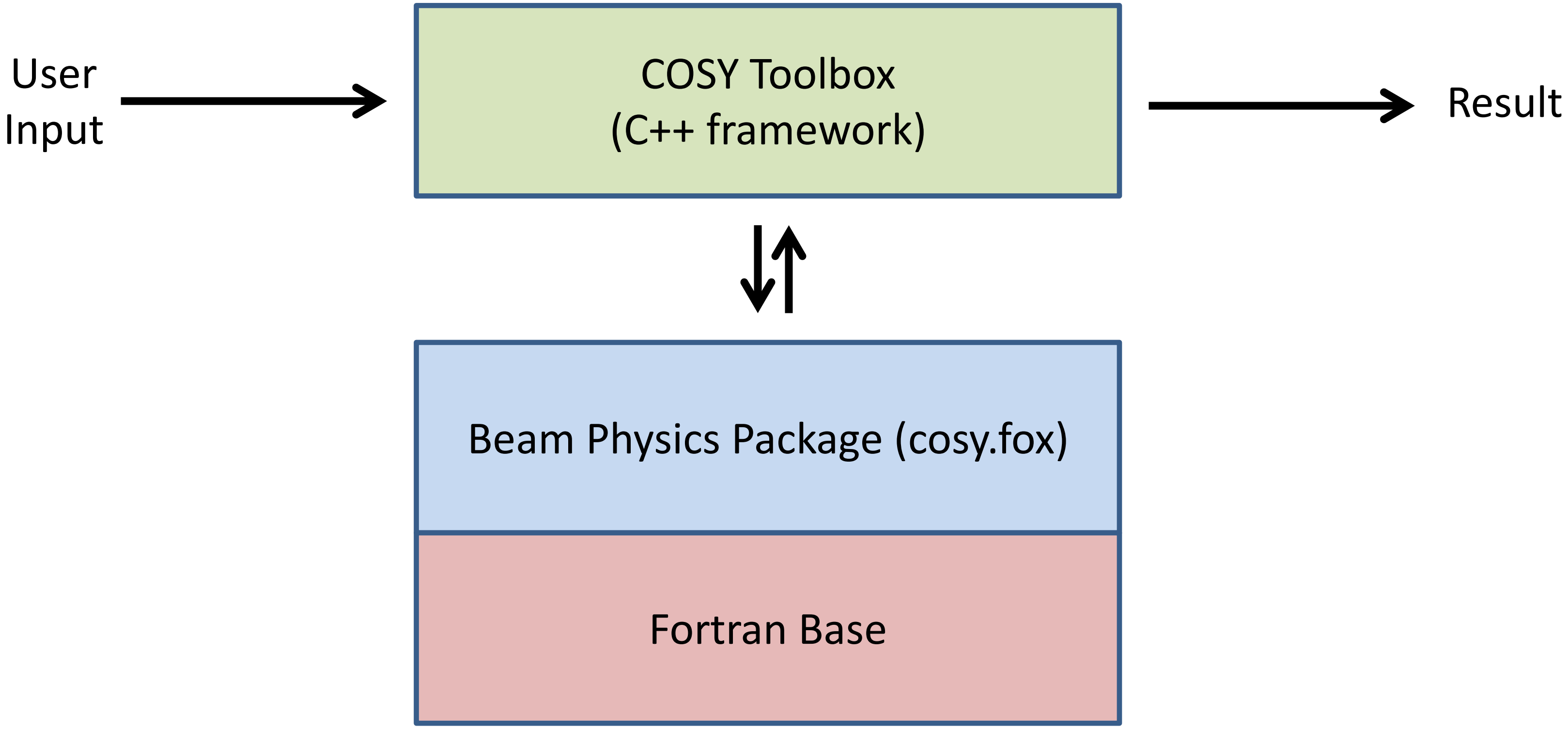
Plot of
COSY ring structure



Optical functions

New method

- New level on top:



User Input

COSY Toolbox (C++ framework)

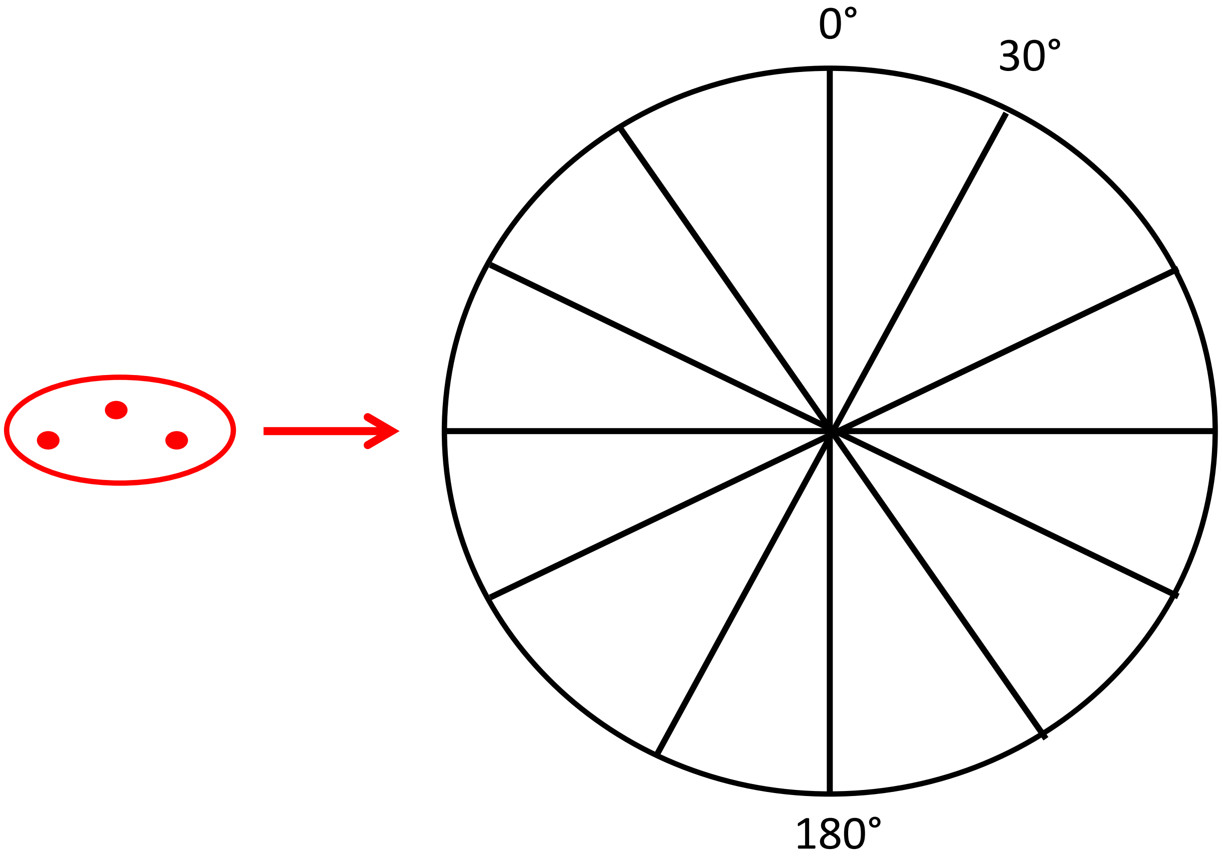
Result

Beam Physics Package (cosy.fox)

Fortran Base

RF-Tracking illustration

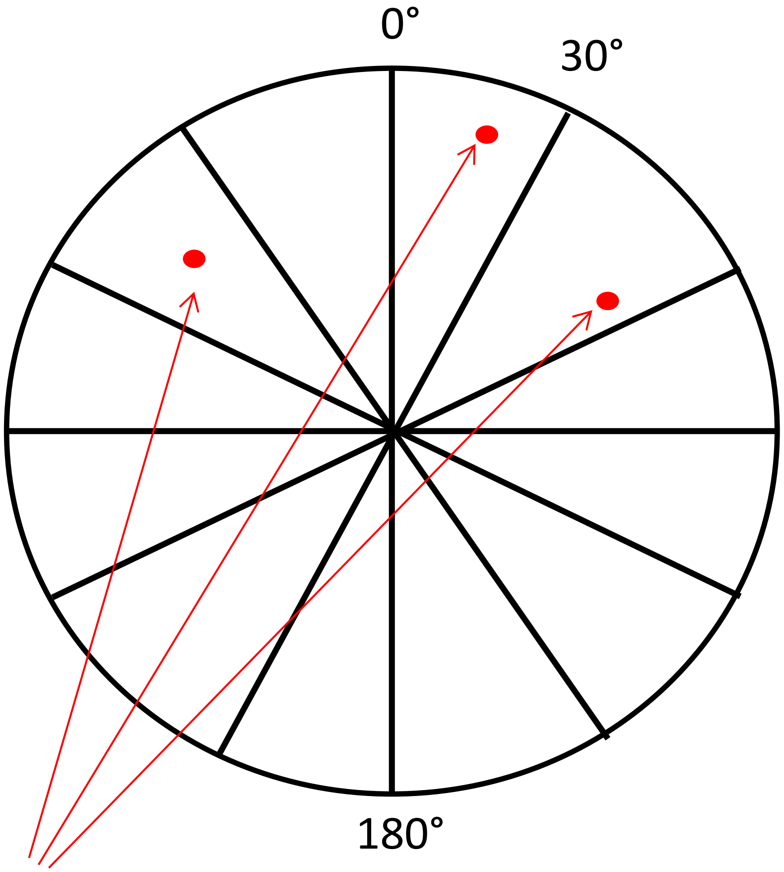
- Example with 12 maps:



Bunch approaching RF map

RF-Tracking illustration

- Example with 12 maps:



Particles are tracked though map corresponding to phase

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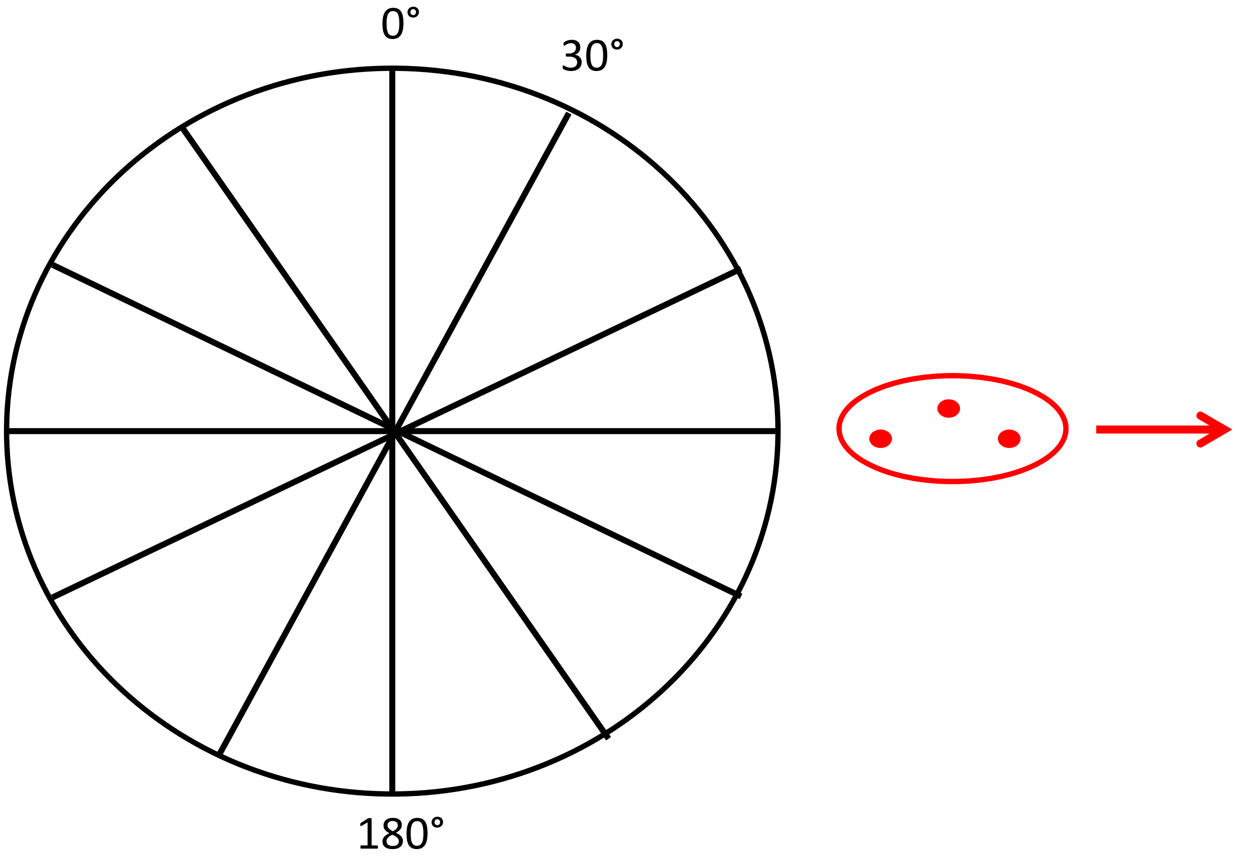
RF-Tracking illustration

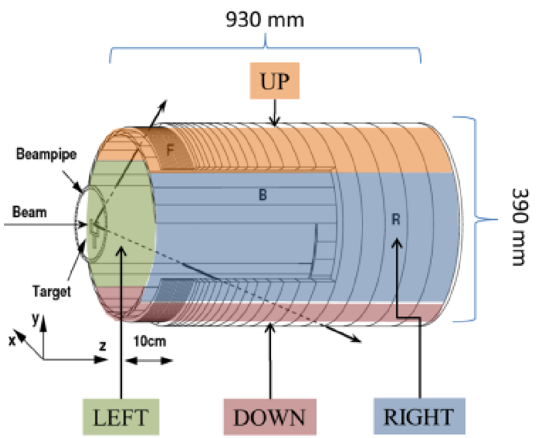
- Example with 12 maps:



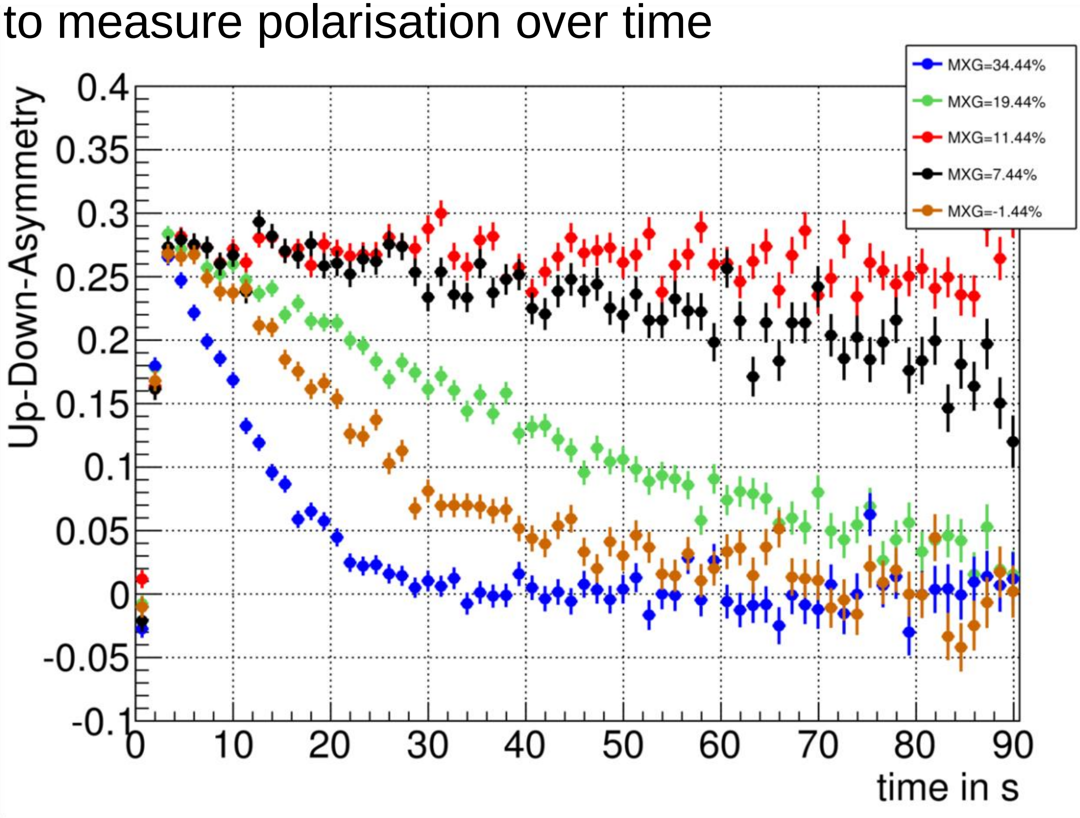
Bunch passed RF map

Spin Coherence Time III

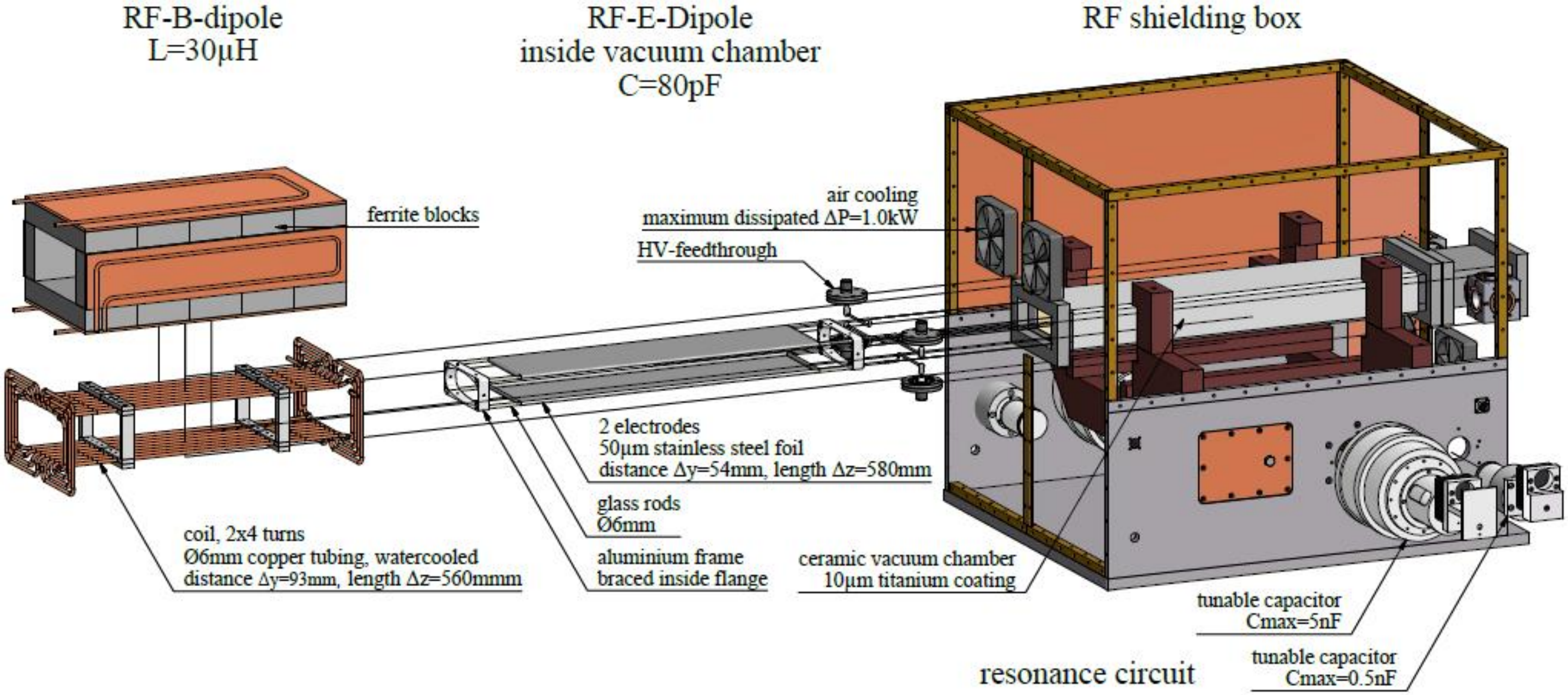
- SCT studies performed during last beam time:
  - Polarised deuterons @ 970 MeV/c
  - Electron-cooled
  - „Heated“ in 1 direction (horizontally or longitudinally)
  - Beam steered on target to measure polarisation over time



- Polarisation evolution for different sextupole configurations



The RF-E×B-Dipole



Courtesy: Sebastian Mey

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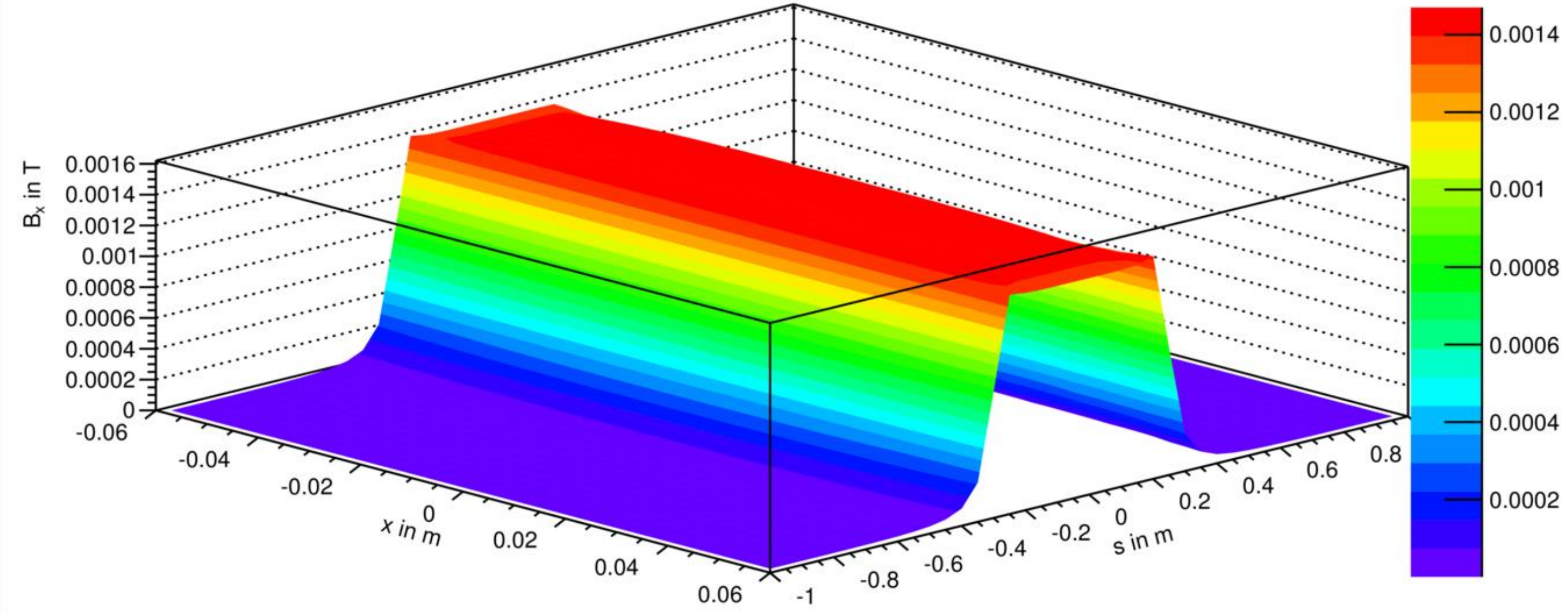
1st step: Field Maps

- This Version: Field maps provided by R. Gebel and S. Mey for the existing RF-WienFilter
    - Static field for maximum current / voltage

- <u>Example for radial magnetic field</u>

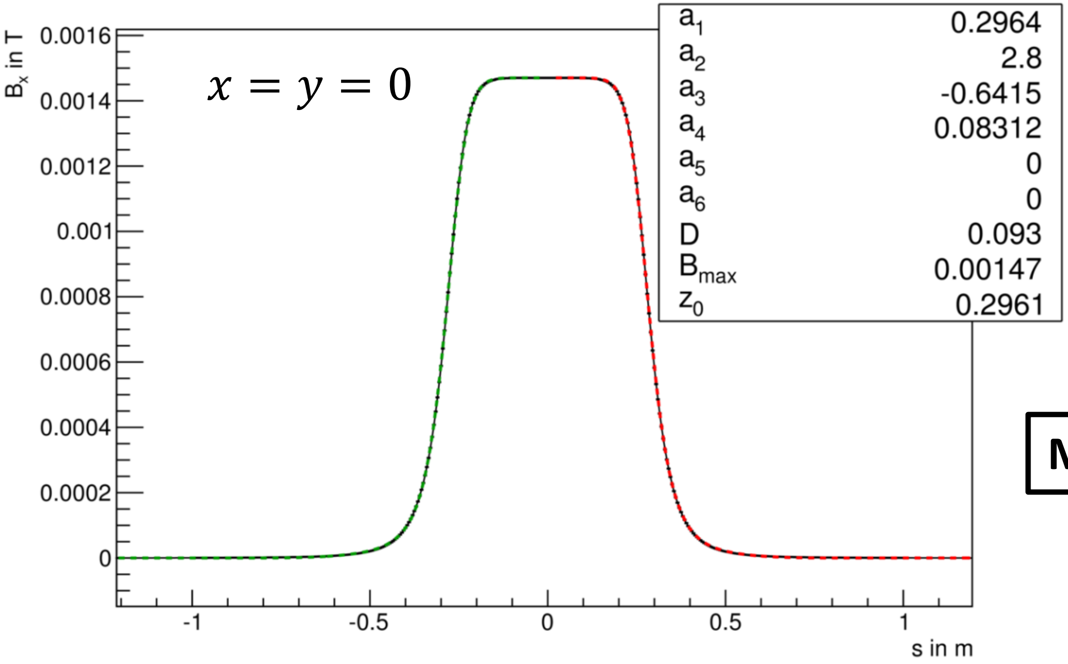


1st step: Field Maps

- Simplification (quasi-static approach):
  - $F(x,s,t) = F(x,s) \cdot \cos(\omega t)$
  - $F(x,s) = F_{max} \cdot f(x) \cdot f(s)$
  - $f(x)$: Polynomial function
  - $f(s)$: Enge functions for entrance and exit

- Field change during one pass is included.

1st step: Field Maps

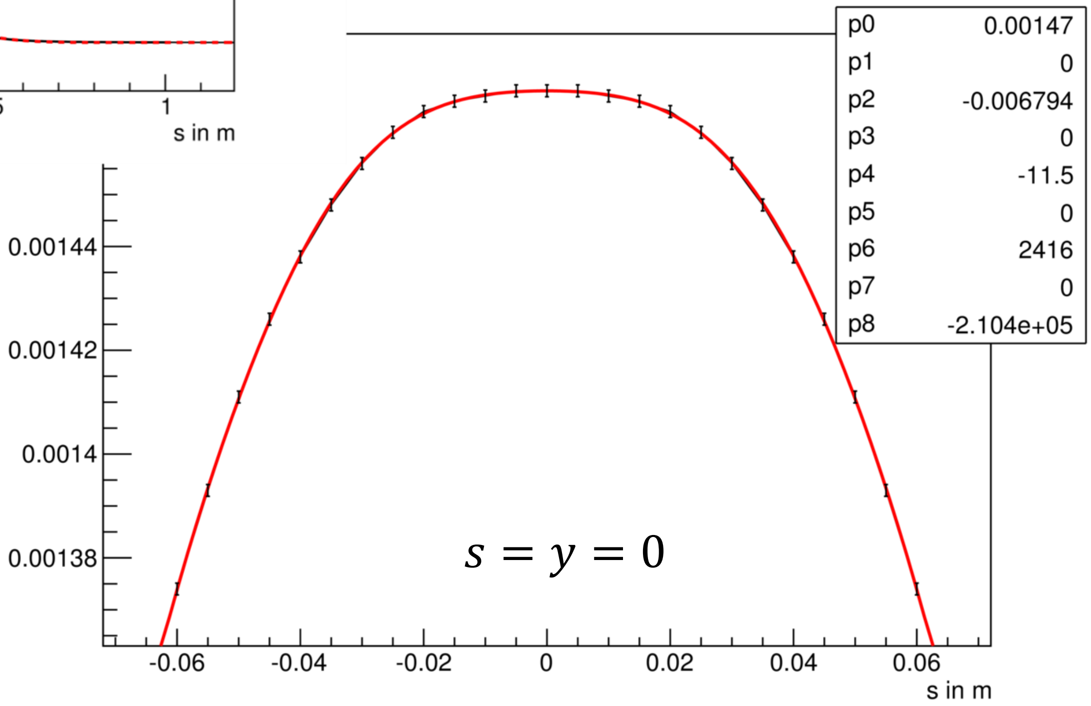


- $F(x,s,t) = F(x,s) \cdot \cos(\omega t)$
- $F(x,s) = F_{max} \cdot f(x) \cdot g(s)$
- $f(x)$: Polynomial function
- $g(s)$: Enge functions

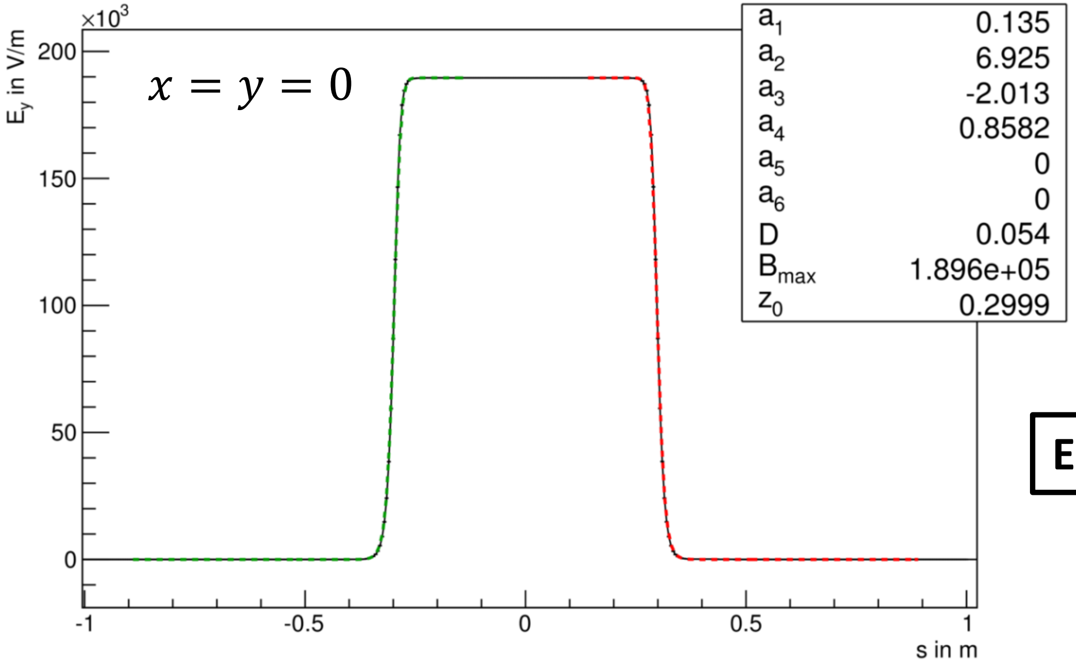
Magnetic

Enge-function:

$$h(z) = \frac{1}{1 + \exp(a_1 + a_2 \cdot \left(\frac{z}{D}\right) + \cdots + a_6 \left(\frac{z}{D}\right)^5}$$



1st step: Field Maps

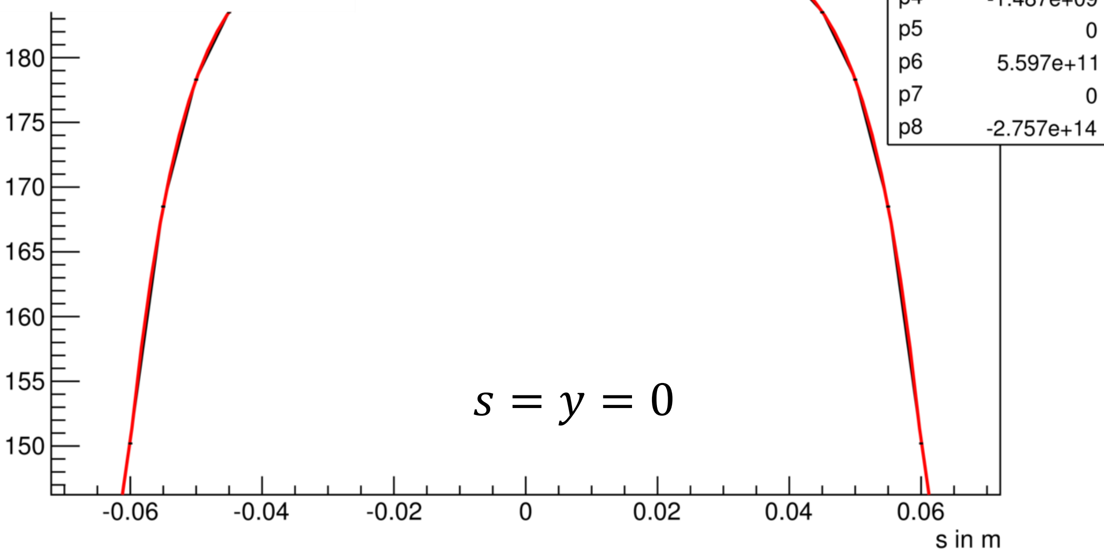


- $F(x,s,t) = F(x,s) \cdot \cos(\omega t)$
- $F(x,s) = F_{max} \cdot f(x) \cdot g(s)$
- $f(x)$: Polynomial function
- $g(s)$: Enge functions

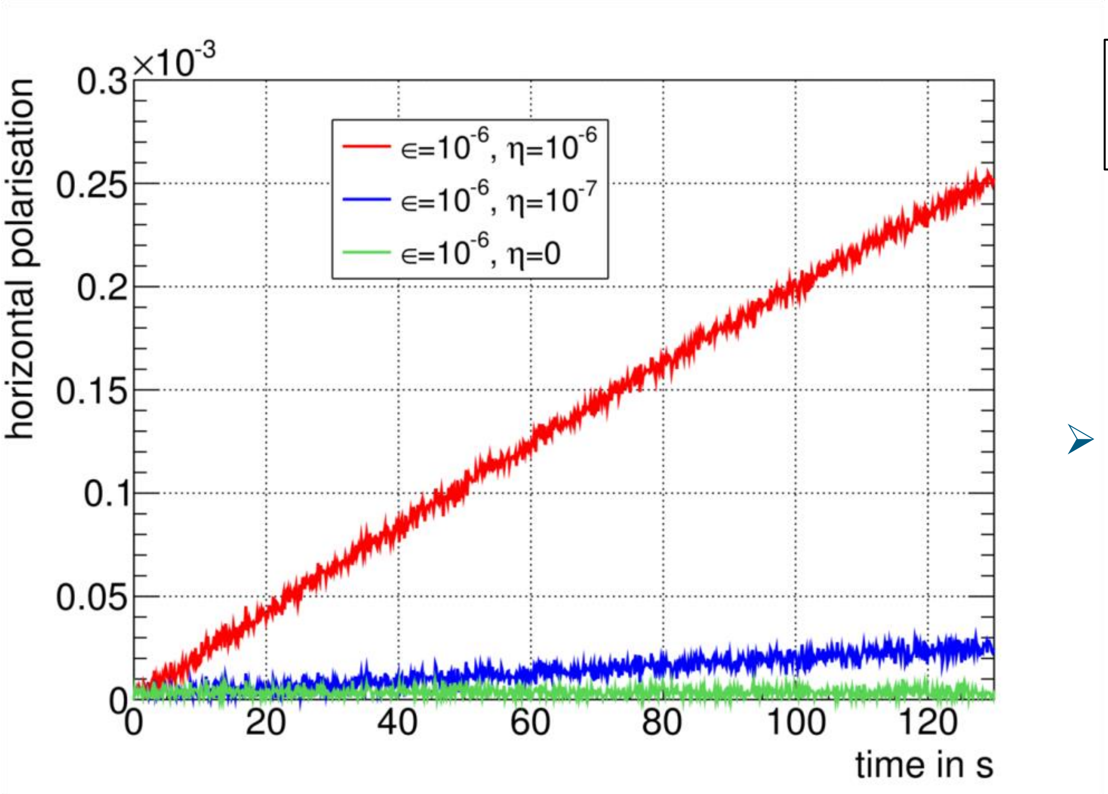
Electric

Enge-function:

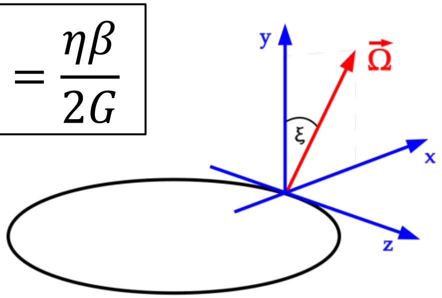
$$h(z) = \frac{1}{1 + \exp\left(a_1 + a_2 \cdot \left(\frac{z}{D}\right) + \dots + a_6 \left(\frac{z}{D}\right)^5\right.}$$



EDM measurements @ COSY



$$\tan\xi = \frac{\eta\beta}{2G}$$



- Buildup per revolution:

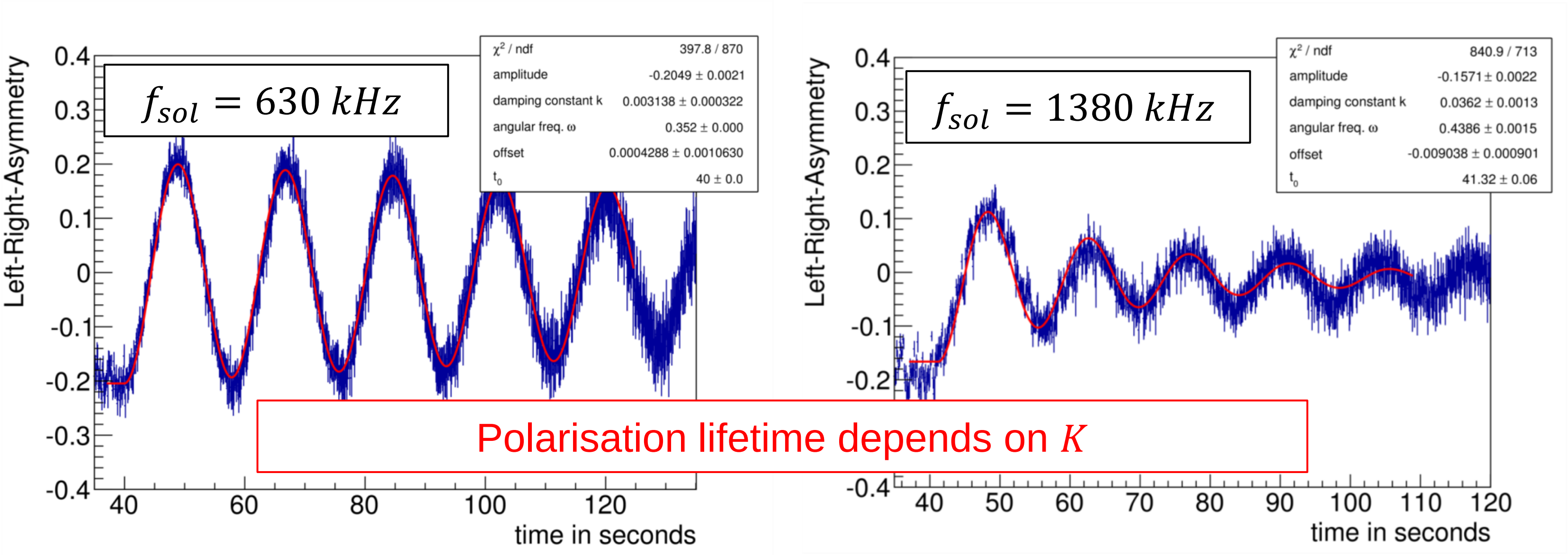
$$\Theta = \frac{\psi\xi}{2} = 4\pi\cdot\frac{\epsilon\xi}{2}$$

Deuterons:

p	ϵ	L	E	B	η	Θ
970 MeV/c	10^{-6}	0.6 m	12.2 kV/m	0.09 mT	10^{-9}	10^{-14}
970 MeV/c	10^{-4}	0.6 m	1.2 MV/m	8.9 mT	10^{-9}	10^{-12}

RF Induced Spin Resonances

- Precursor experiment: RF-ExB-resonance to build-up EDM signal
- First studies using an RF-Solenoid to investigate induced spin resonances
- Resonance condition: $f_{sol} = |K + G\gamma| \cdot f_{rev}$



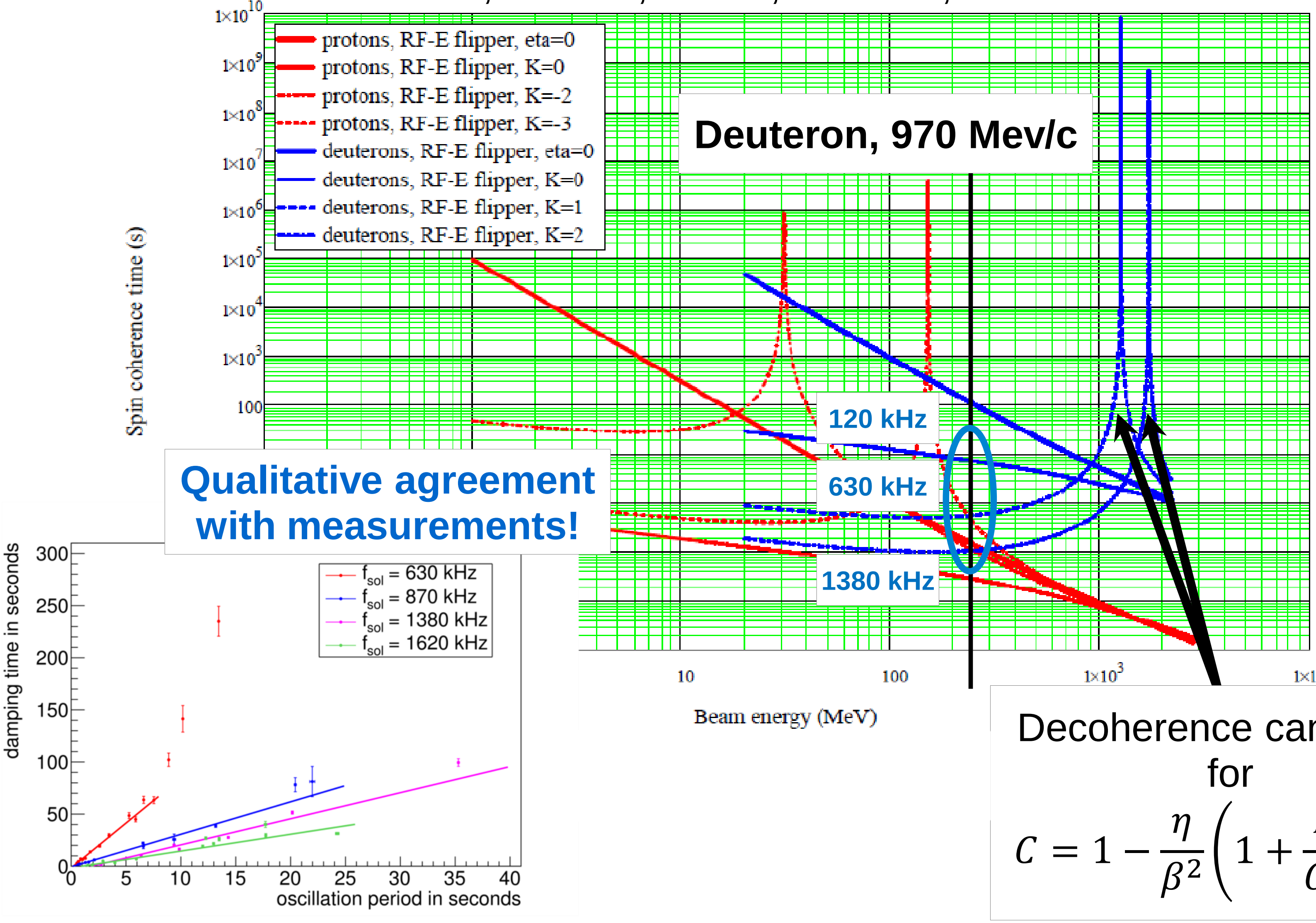
χ^2 / ndf	397.8 / 870
amplitude	-0.2049 ± 0.0021
damping constant k	0.003138 ± 0.000322
angular freq. ω	0.352 ± 0.000
offset	0.0004288 ± 0.0010630
t_0	40 ± 0.0

χ^2 / ndf	840.9 / 713
amplitude	-0.1571 ± 0.0022
damping constant k	0.0362 ± 0.0013
angular freq. ω	0.4386 ± 0.0015
offset	-0.009038 ± 0.000901
t_0	41.32 ± 0.06

Polarisation lifetime depends on K

Theoretical prediction

Lehrach, Lorentz, Morse, Nikolaev, Rathmann: DSPIN-2011



Deuteron, 970 Mev/c

120 kHz

630 kHz

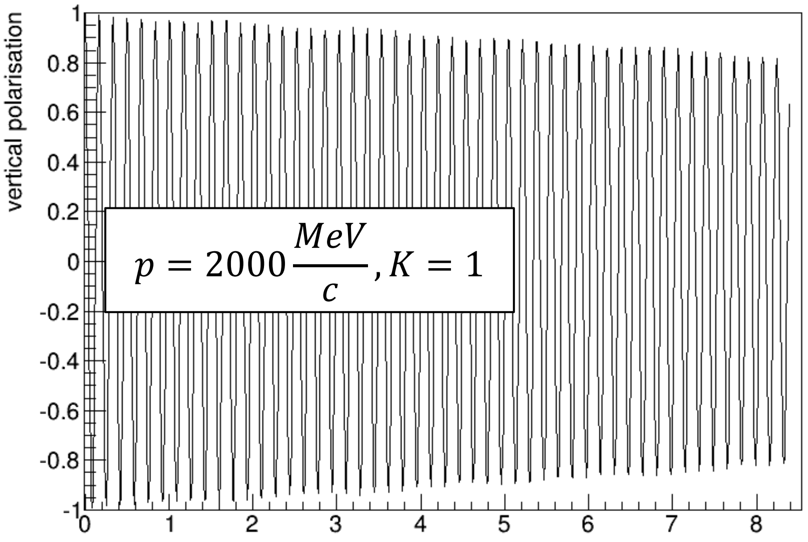
1380 kHz

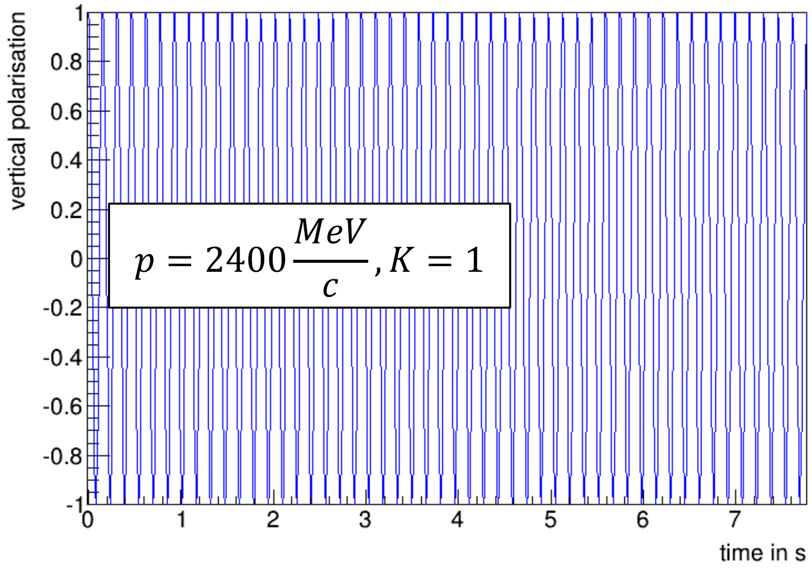
Qualitative agreement with measurements!

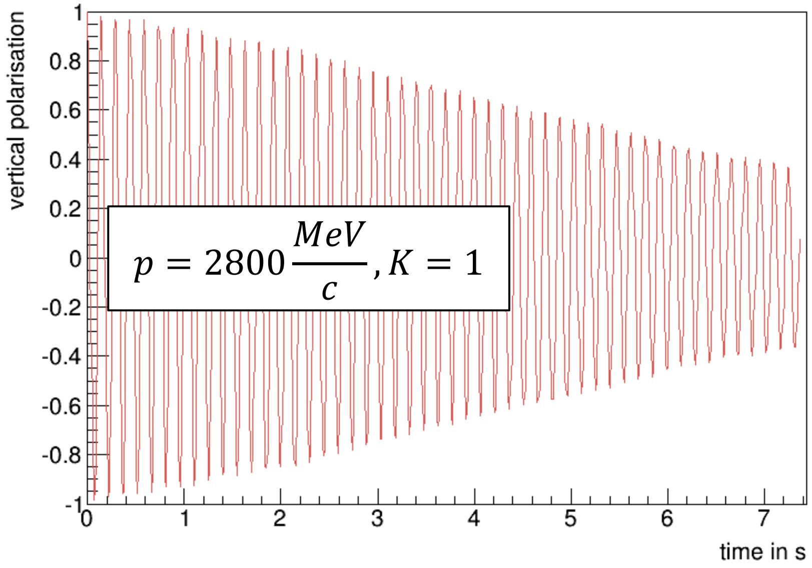
Decoherence cancelled for

$$C = 1 - \frac{\eta}{\beta^2}\left(1 + \frac{K}{G\gamma}\right) = 0$$

Simulations of induced resonance







$$C = 1 - \frac{\eta}{\beta^2}\left(1 + \frac{K}{G\gamma}\right) = 0$$

- ➢ fulfilled for $p \approx 2402\ MeV/c$
- ➢ Important for different ideas of EDM measurements in storage rings.

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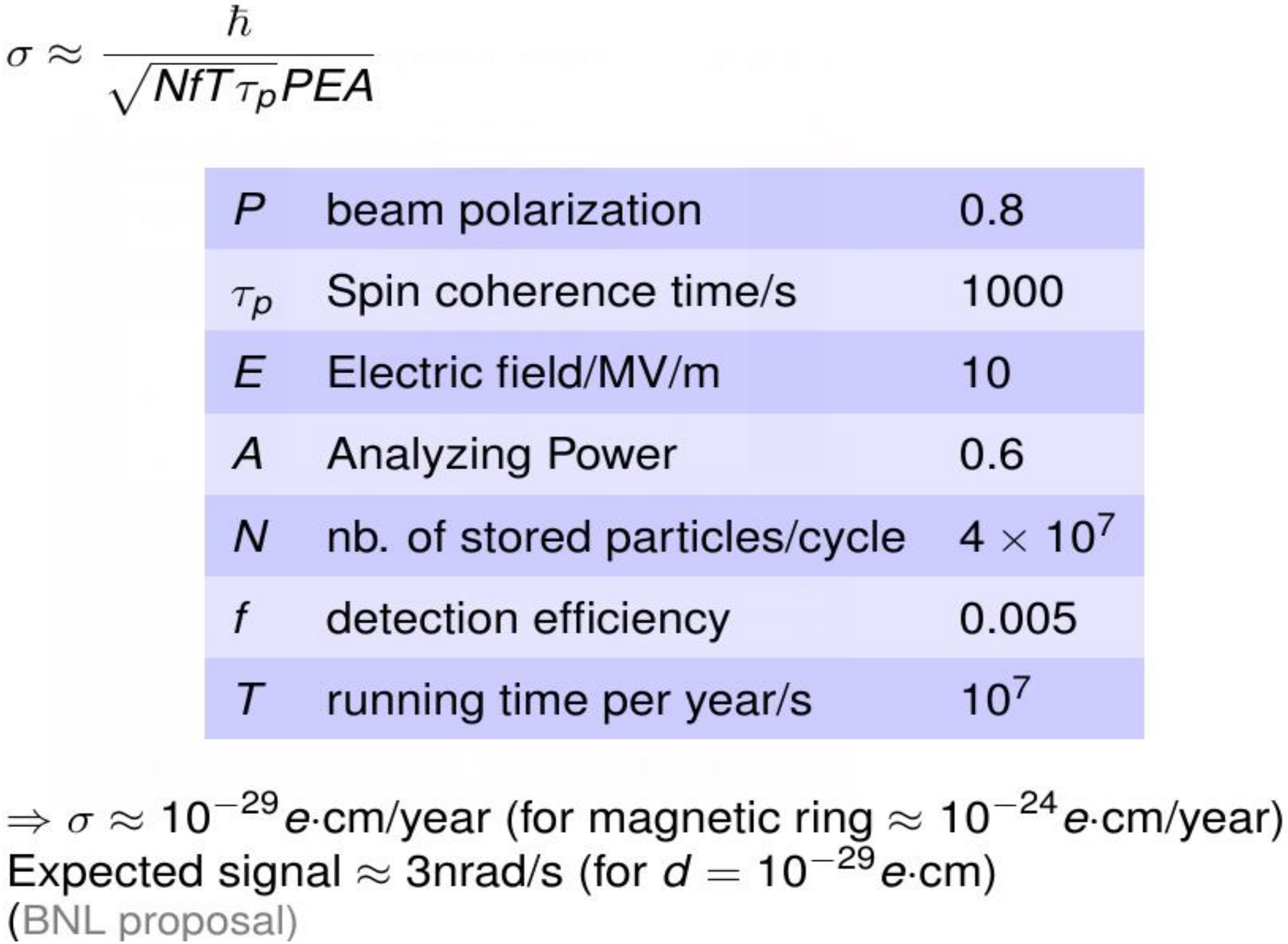
Statistical Sensitivity for electric/combined-ring



$$\sigma \approx \frac{\hbar}{\sqrt{NfT\tau_p}PEA}$$

P	beam polarization	0.8
τ_p	Spin coherence time/s	1000
E	Electric field/MV/m	10
A	Analyzing Power	0.6
N	nb. of stored particles/cycle	4×10^7
f	detection efficiency	0.005
T	running time per year/s	10^7

$\Rightarrow \sigma \approx 10^{-29} e$·cm/year (for magnetic ring $\approx 10^{-24} e$·cm/year)
Expected signal ≈ 3nrad/s (for $d = 10^{-29} e$·cm)
(BNL proposal)

Statistical Sensitivity for magnetic ring (COSY)

$$\sigma \approx \frac{\hbar}{2} \frac{G\gamma^2}{G+1} \frac{U}{E \cdot L} \frac{1}{\sqrt{NfT\tau_p PA}}$$

G	anomalous magnetic moment	
γ	relativistic factor $p = 1\mathrm{GeV}/c$	1.13
U	circumference of COSY	180 m
$E \cdot L$	integrated electric field	$0.1 \cdot 10^6$ V
N	nb. of stored particles/cycle	$2 \cdot 10^9$

$\Rightarrow \sigma \approx 10^{-25} e{\cdot}\mathrm{cm/year}$

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Systematics

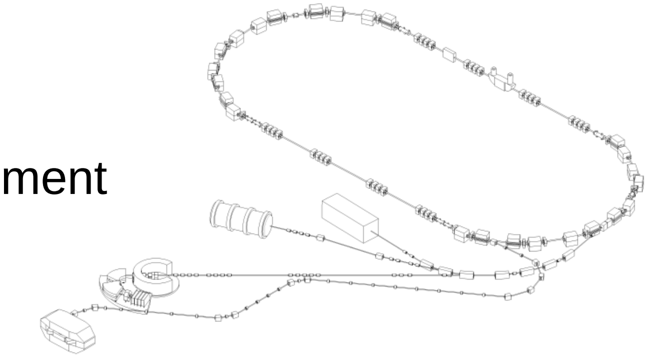
One major source:
Radial B field mimics an EDM effect:

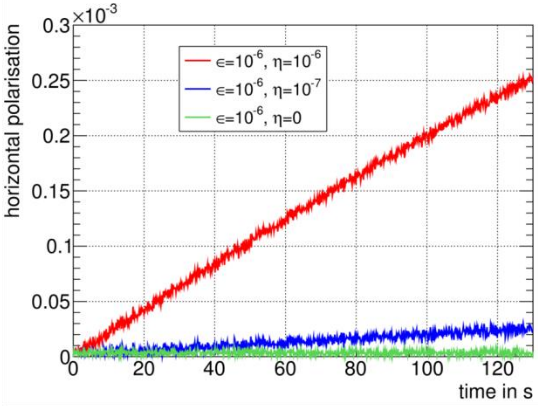
- Difficulty: even small radial magnetic field, B_r can mimic EDM effect if :$\mu B_r \approx dE_r$
- Suppose $d = 10^{-29} e$·cm in a field of $E = 10\text{MV/m}$
- This corresponds to a magnetic field:
  $$B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22}e\mathrm{V}}{3.1 \cdot 10^{-8}e\mathrm{V}/\mathrm{T}} \approx 3 \cdot 10^{-17}\mathrm{T}$$
  (Earth Magnetic field $\approx 5 \cdot 10^{-5}$ T)

Solution: Use two beams running clockwise and counter clockwise, separation of the two beams is sensitive to B_r

Summary & Outlook

- EDM measurements in storage rings
  - Feasibility studies and precursor experiment at COSY/Jülich





- EDM related polarisation build-up using induced spin resonance
  - RF-ExB-Flipper (→ talk: S.Mey)
- *Outlook: systematic studies concerning beam alignment and field quality*

- Preservation of polarisation mandatory
  - Sextupole corrections
- *Outlook: further investigation of SCT*