# Tracking Studies towards EDM Measurements at COSY

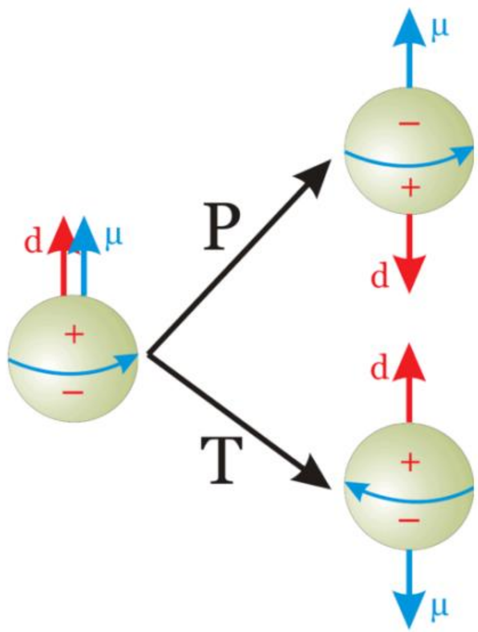
2015-02-23 | Marcel Rosenthal

# 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
  - False signal due to magnet imperfections

# CP-Violating permanent EDMs

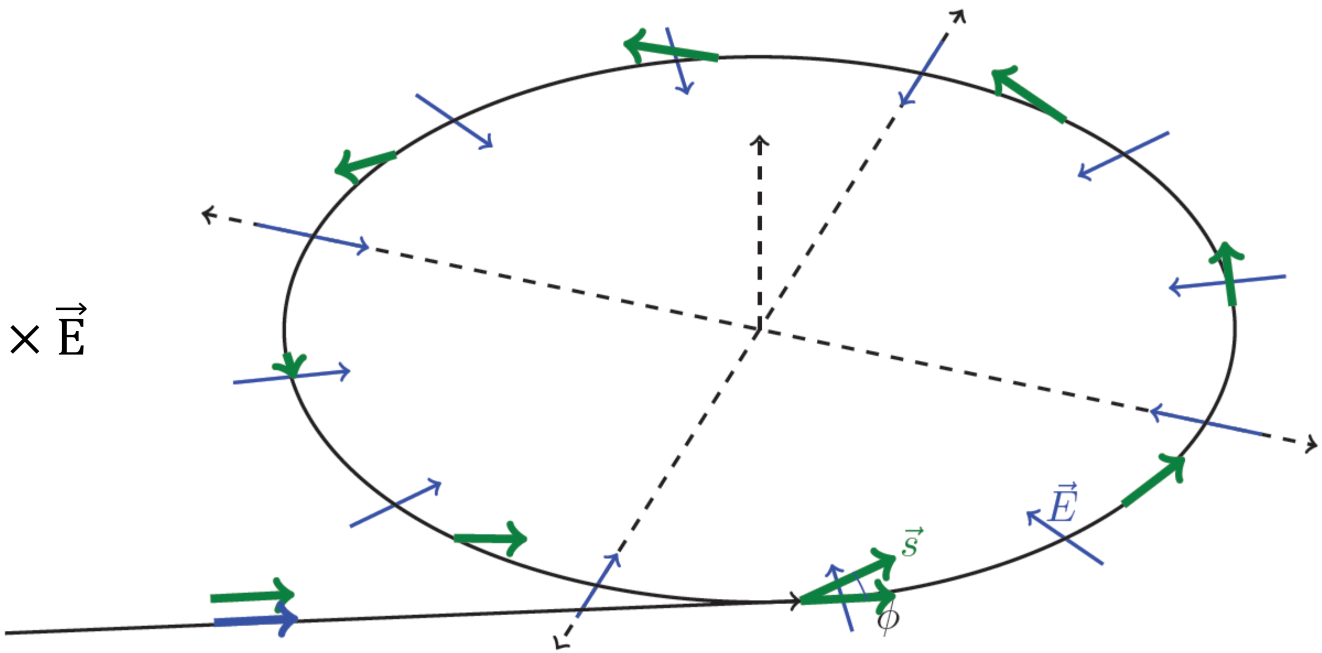



- Electric Dipole Moments:
  - Charge separation
  - Fundamental property
- Permanent EDMs are P- and T-violating
  - CPT-Theorem: CP-Violation
- Known CP-Violation not sufficient to explain Matter-Antimatter-Asymmetry in universe
- Search for new sources of CP-Violation ($\Theta$-term, BSM) by measuring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

# EDM measurements in storage rings

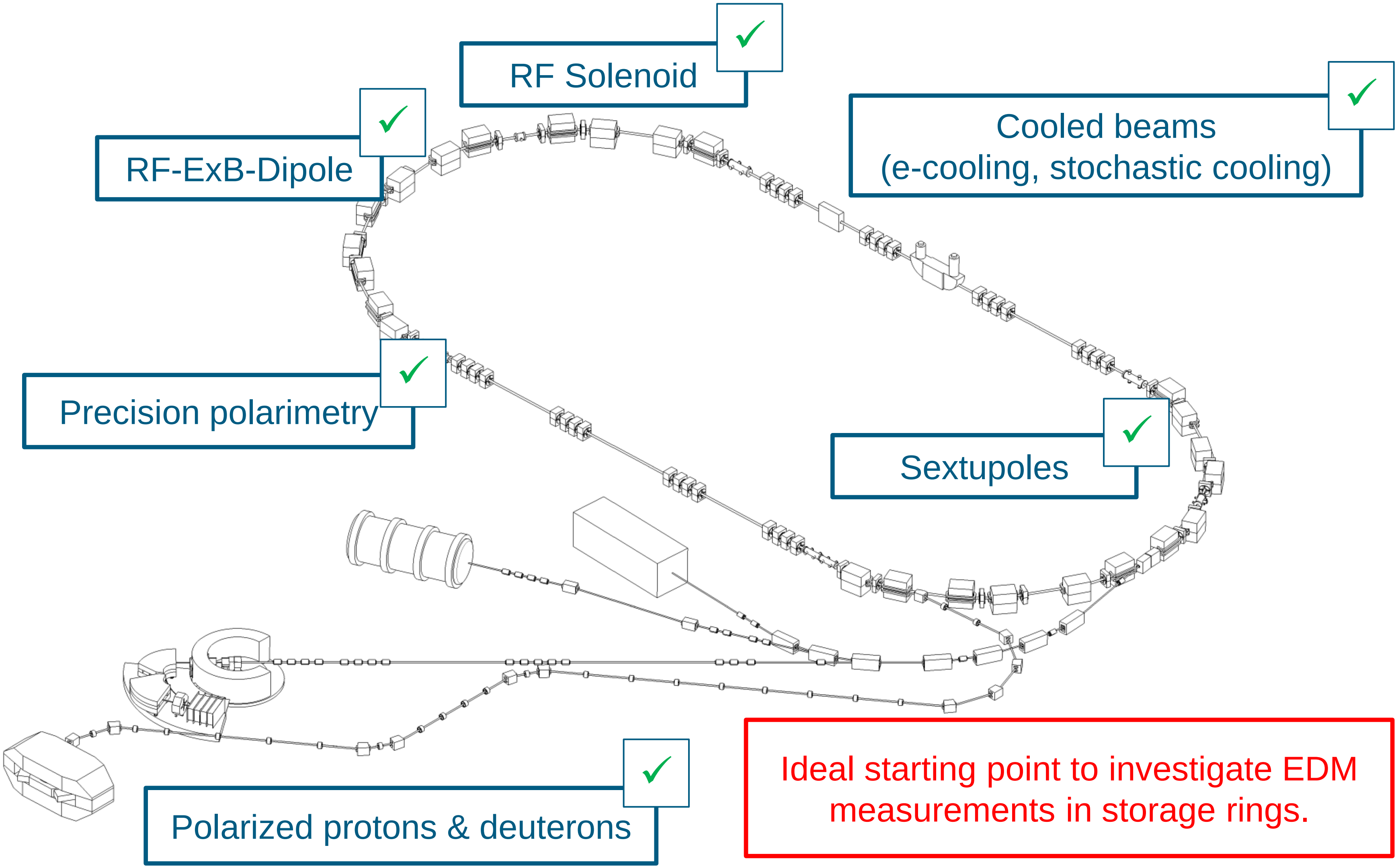
JÜLICH FORSCHUNGSZENTRUM

$$\frac{d\vec{S}}{dt} \propto d \cdot \vec{S} \times \vec{E}$$




- 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




Ideal starting point to investigate EDM measurements in storage rings.

# Thomas-BMT-Equation

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

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

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

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

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

| | G |
|---|---|
| Proton | 1.792847357 |
| Deuteron | -0.142561769 |

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

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

# Thomas-BMT-Equation (pure magnetic)

JÜLICH FORSCHUNGSZENTRUM

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

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

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

- Cooler Synchrotron Jülich is conventional pure magnetic ring:
  - Spin precesses around vertical guiding field.
    - Invariant Spin Axis (Spin Closed Orbit) is vertical
  - 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 $\vec{\Omega}_{MDM} = 0$
    - Not applicable in pure magnetic ring

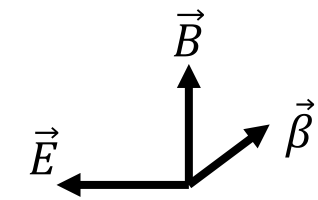
Mitglied der Helmholtz-Gemeinschaft

# 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

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

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




- Device is EDM transparent ⇒ no tilt ($\xi = 0$)
  - Polarization signal:

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

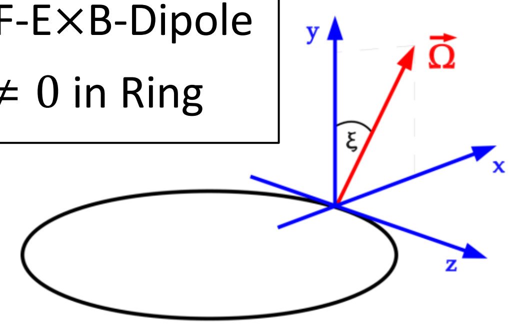
$$\theta \approx \frac{\psi\xi}{2}$$

$\psi$: max. spin rotation in RF field

$\xi$: EDM tilt

$\tan\xi = 0$ in RF-E×B-Dipole

$\tan\xi = -\frac{\eta\beta}{2G} \neq 0$ in Ring



# Outline

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- **Part 2: Simulations**
  - Simulation framework
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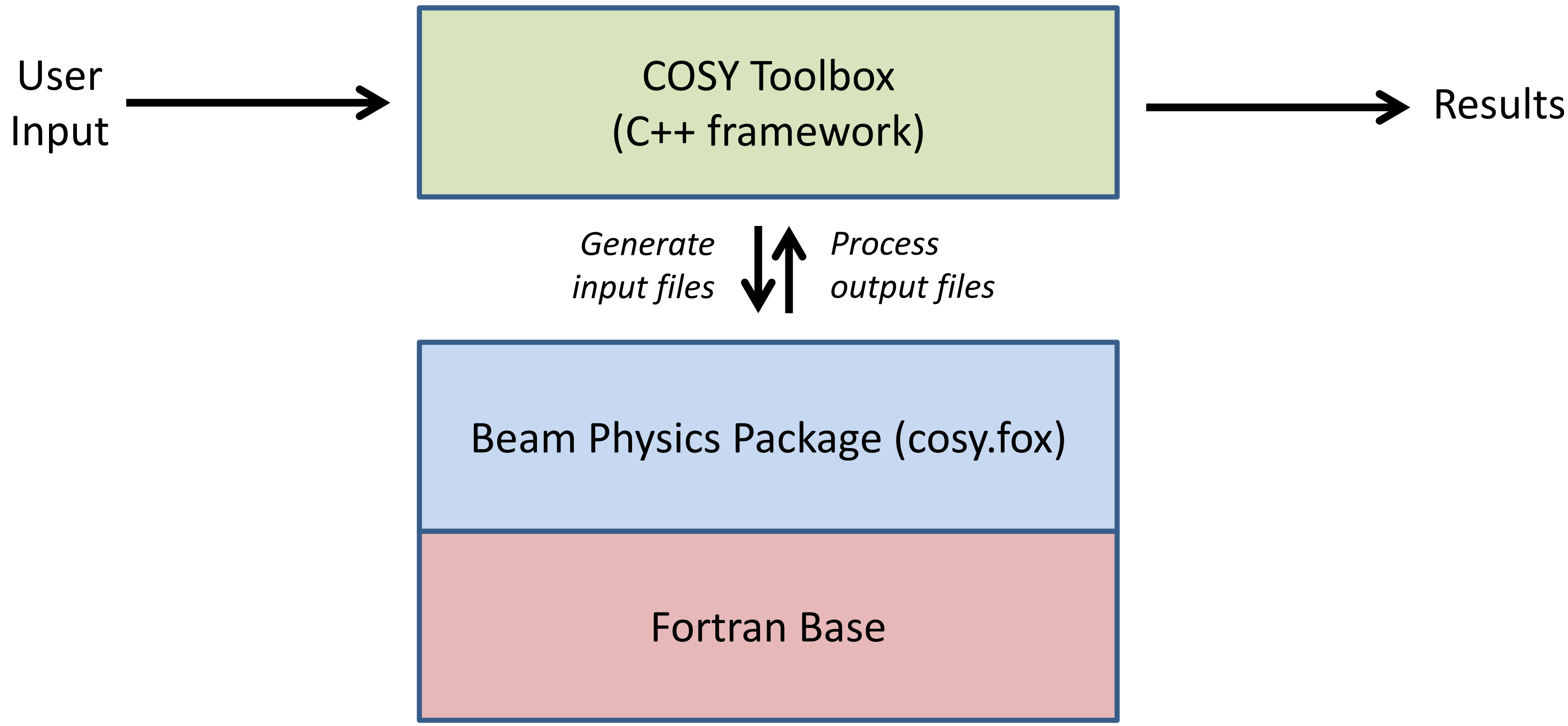
# Simulation framework

- Tracking by COSY Infinity (DA-based transfer map calculation)
- New package on top of COSY Infinity



# COSY Toolbox

COSY Lattice

COSY INFINITY

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

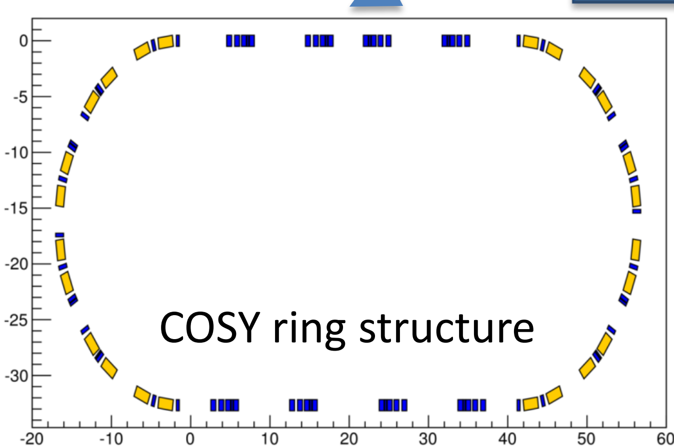
COSY Toolbox

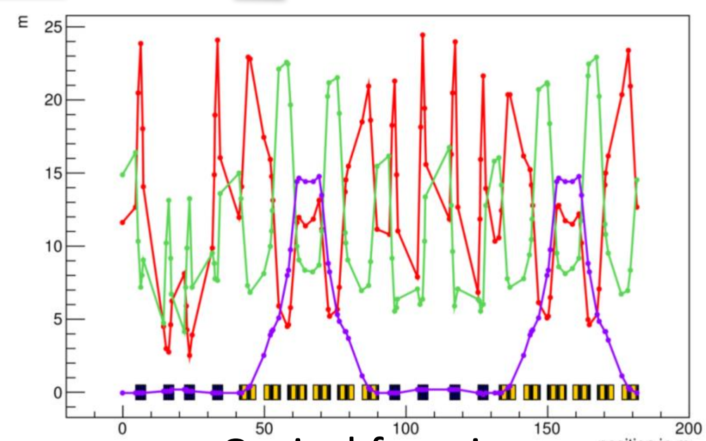
Armadillo

- linear algebra operations
- SVD, pseudo-inverse

ROOT

- plotting
- storage (ROOT files/trees)



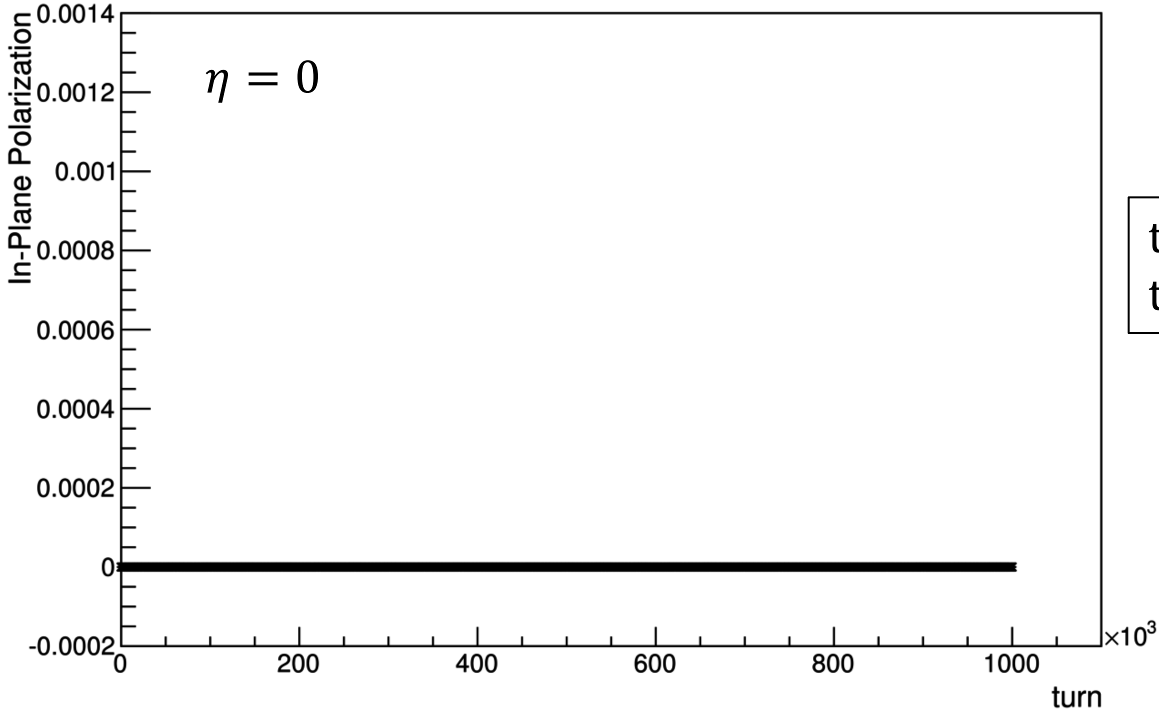




Optical functions

# Measurement Principle @ COSY



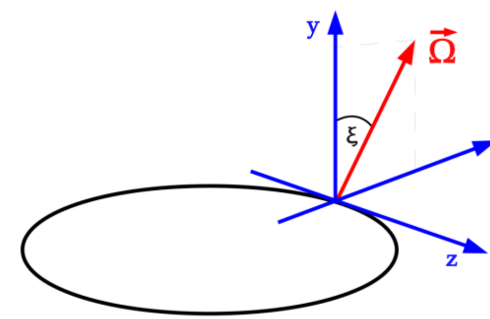
- Excite EDM related spin resonance
- Ideal ring and RF-E×B-Dipole → no buildup without EDM
- Simulated: Polarized deuteron, $p = 970\ MeV/c$
  RF-E×B-Dipole: $B = 0.1\ mT, l = 0.6\ m$




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

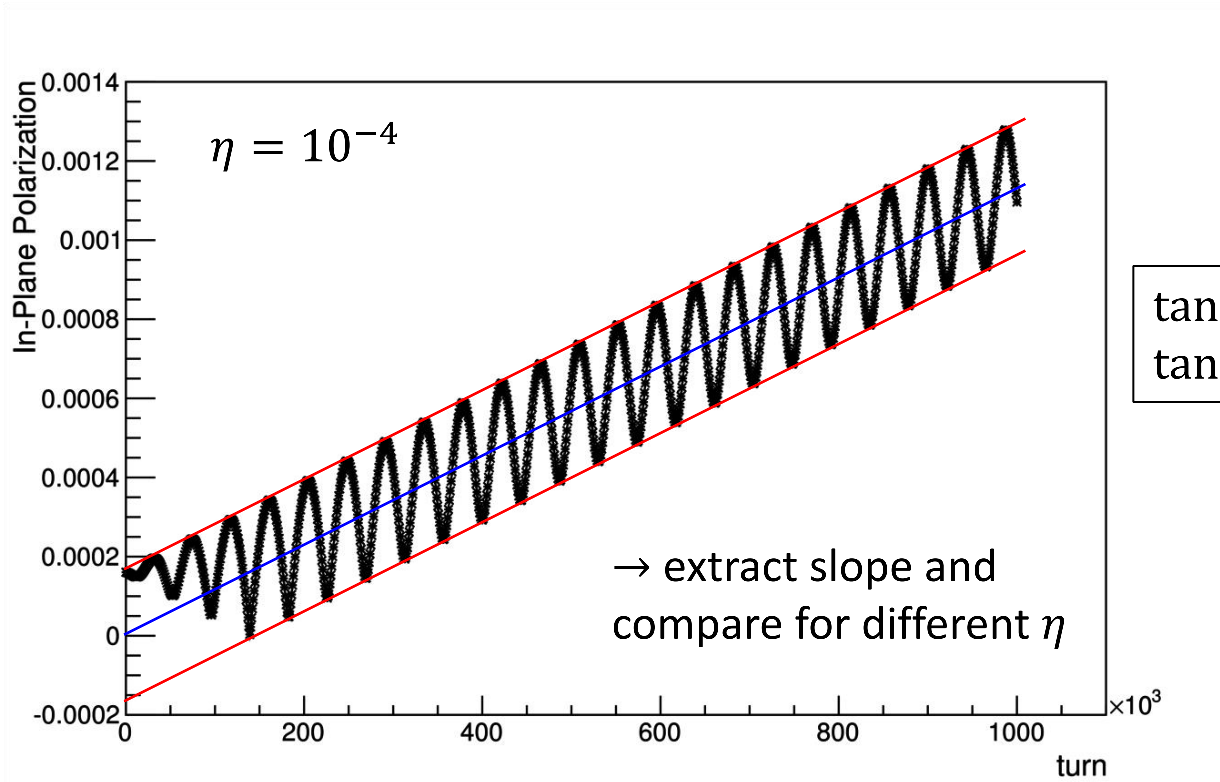
$$\theta \approx \frac{\psi\xi}{2}$$

| |
|---|
| $\tan\xi = 0$ in RF-ExB-Dipole |
| $\tan\xi = 0$ in Ring |



# Measurement Principle @ COSY

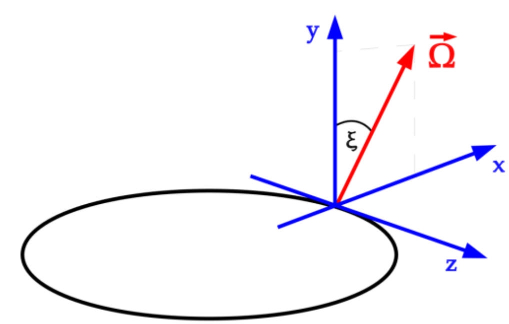
- Excite EDM related spin resonance
- Ideal ring and RF-E×B-Dipole → slow buildup with EDM
- Simulated: Polarized deuteron, $p = 970\ MeV/c$
  RF-E×B-Dipole: $B = 0.1\ mT, l = 0.6\ m$




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

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

$\tan\xi = 0$ in RF-ExB-Dipole
$\tan\xi = 0$ in Ring



# Measurement Principle @ COSY

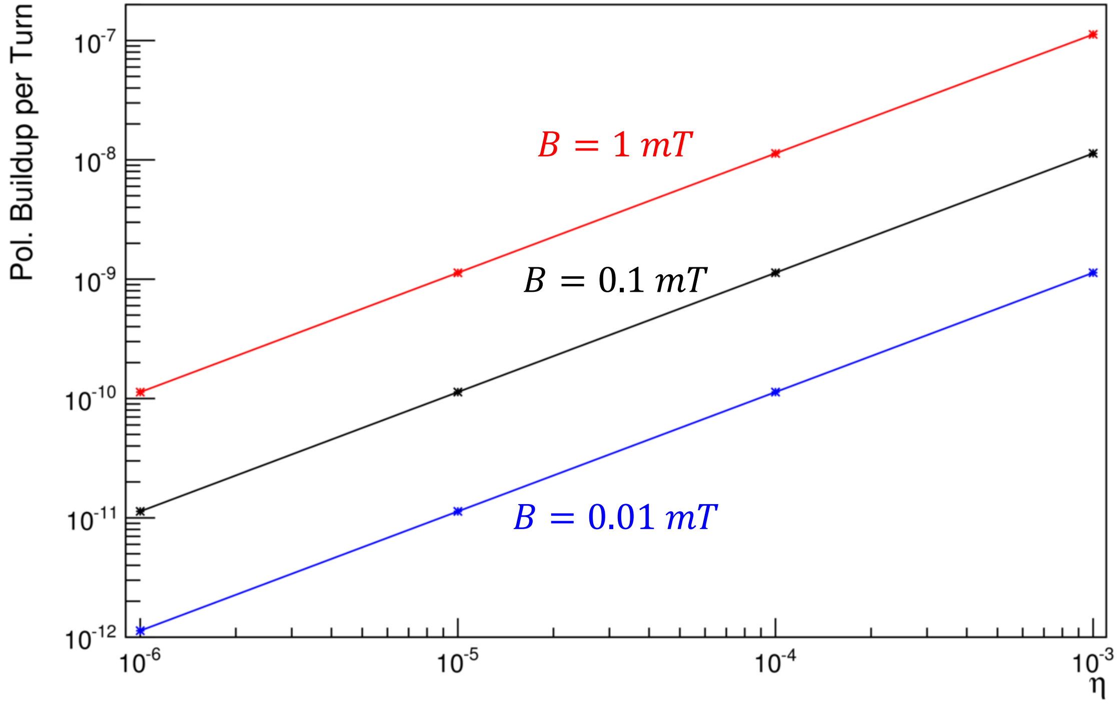
- Buildup-rate proportional to
  - EDM magnitude
  - Field strengths of RF-E×B-Dipole

$$\eta \approx 10^{-4} \leftrightarrow d \approx 5 \cdot 10^{-19} \text{e cm}$$

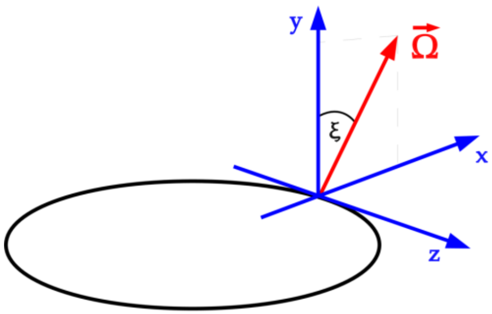
$$\tan \xi = -\frac{\eta\beta}{2G}$$

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

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

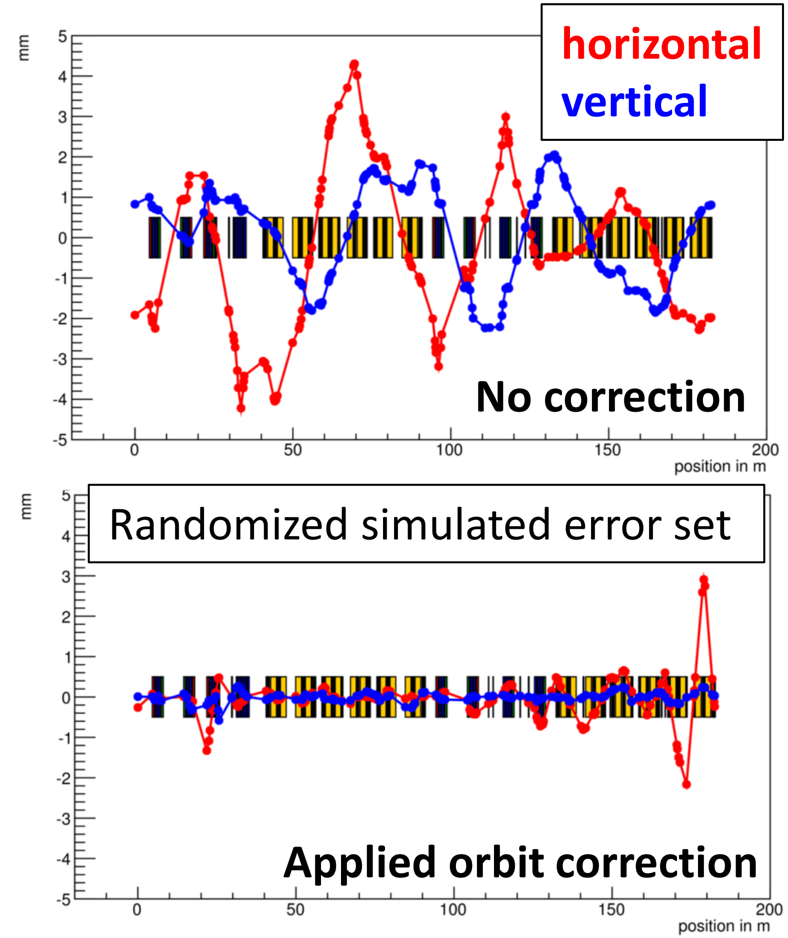



$\tan \xi = 0$ in RF-ExB-Dipole
$\tan \xi = 0$ in Ring



# Misalignments

- Up to now only the ideal machine was demonstrated
- Misalignments and field errors can introduce fake EDM like signals
  - Tilt of Invariant Spin Axis at location of RF-ExB-Dipole
  - Rotation of RF-ExB-Dipole itself
  - Phasespace-Motion
- COSY main magnets:
  - 24 dipoles
  - 56 quadrupoles
- Orbit diagnosis & correction:
  - ~60 beam position monitors
  - ~40 correctors



# Misalignments

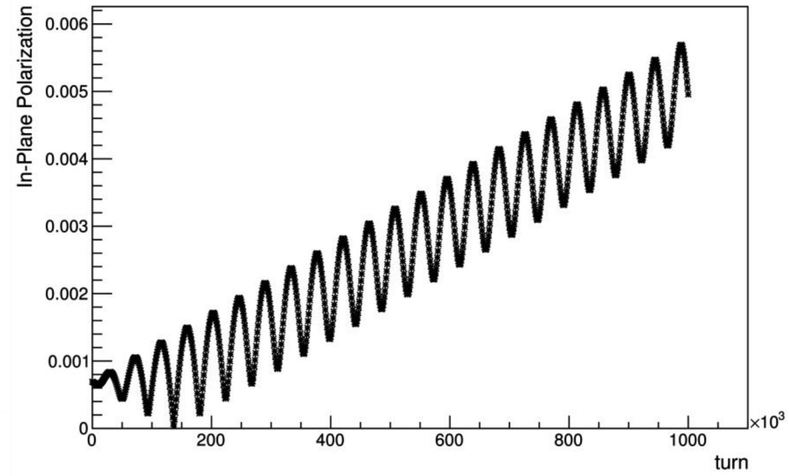
- In this talk, focus on misalignments in the ring:
  - Introduction of radial fields by
    vertical offsets of focusing quadrupoles

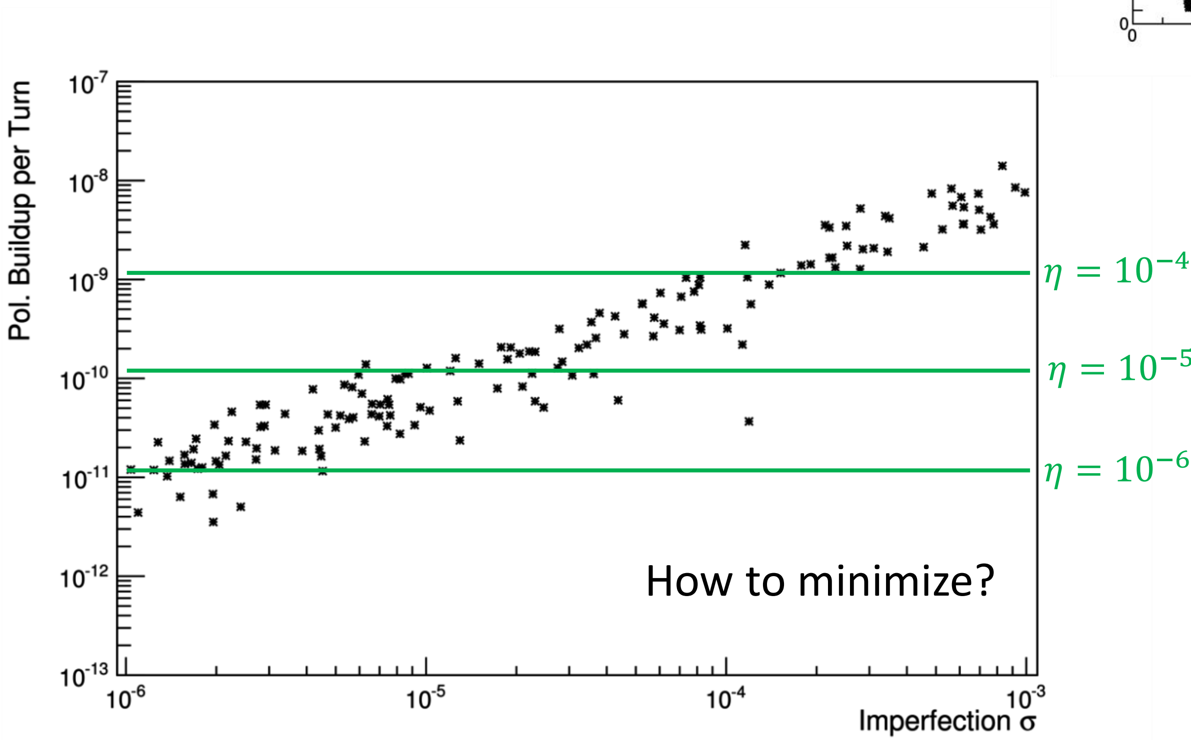
- Method:
  - Random Gaussian distribution of misalignment errors with
    $\sigma = 10^{-6} .. 10^{-3}$ meter (or radian respectively)
  - Study of correction possibilities with existing orbit correction system.

- Correction algorithm in this study:
  - „Best corrector"-method:
    - Select corrector with largest influence
    - Correct orbit
    - Select next corrector …

# Fake-EDM-signal

- EDM turned off in simulations
- Random vertical quadrupole offsets create fake EDM signal

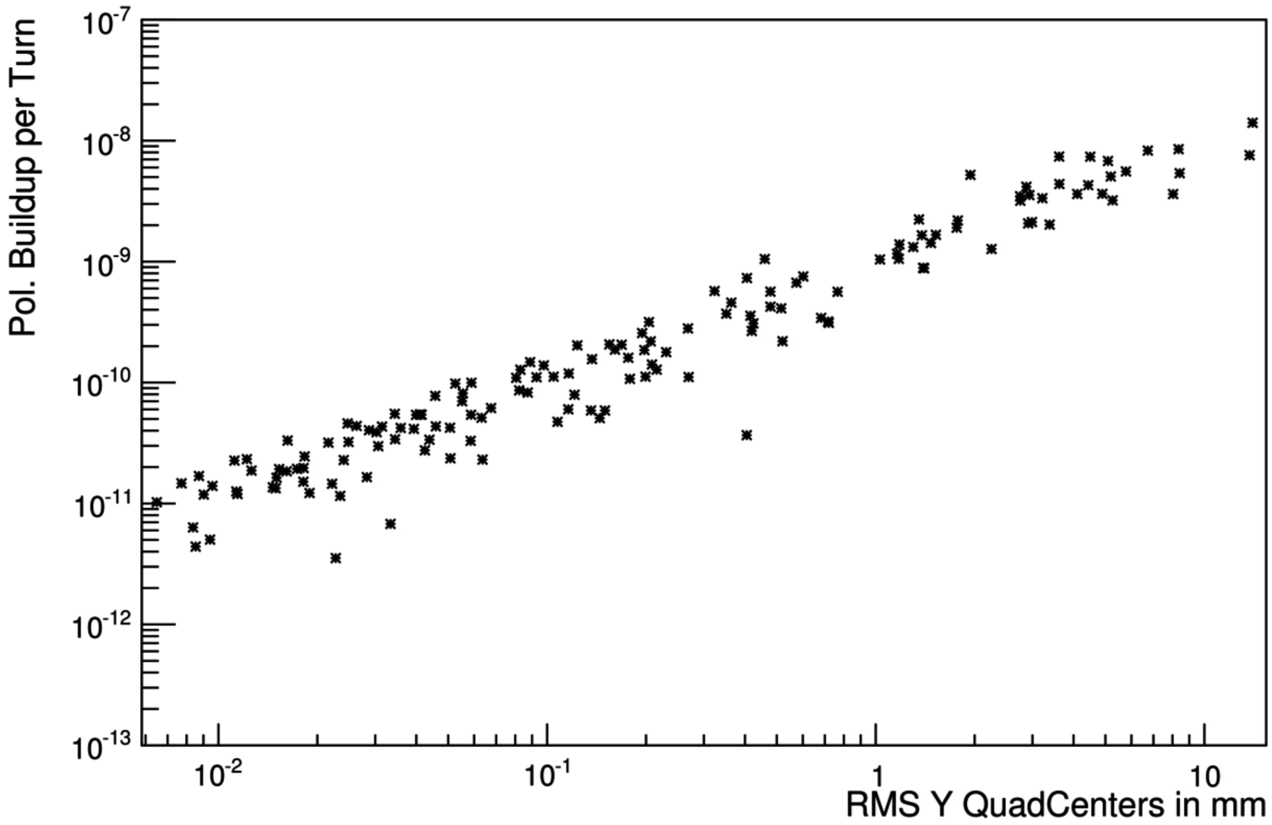



- Systematic limit:
  - $10^{-19}$ e cm for $\sigma = 0.1$ mm

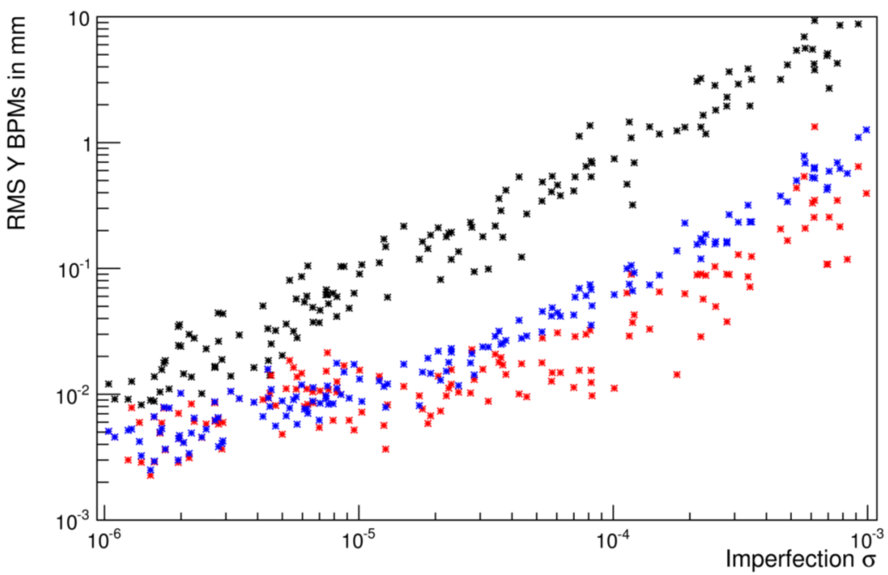
# Polarization buildup and orbit offsets

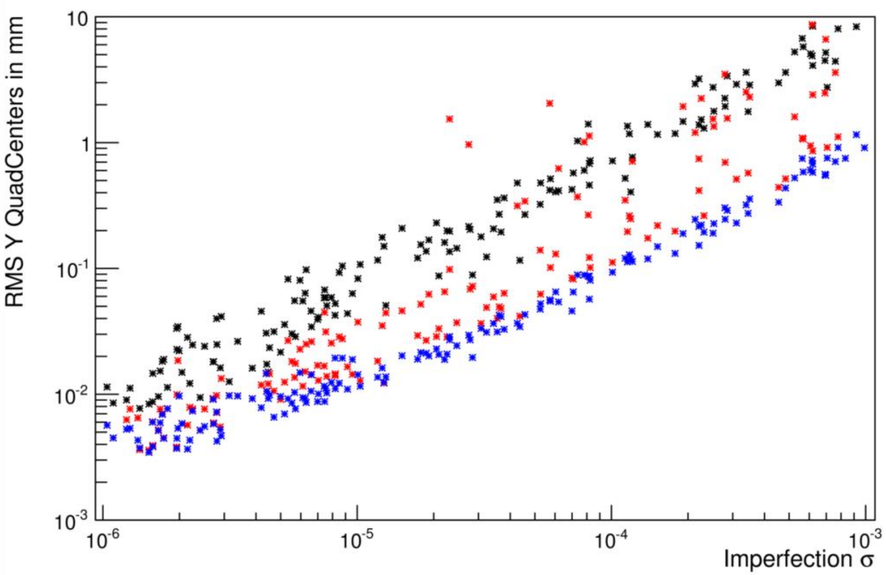
- Investigate correlation of vertical orbit offsets at quadrupole centers and polarization buildup



# Orbit Correction

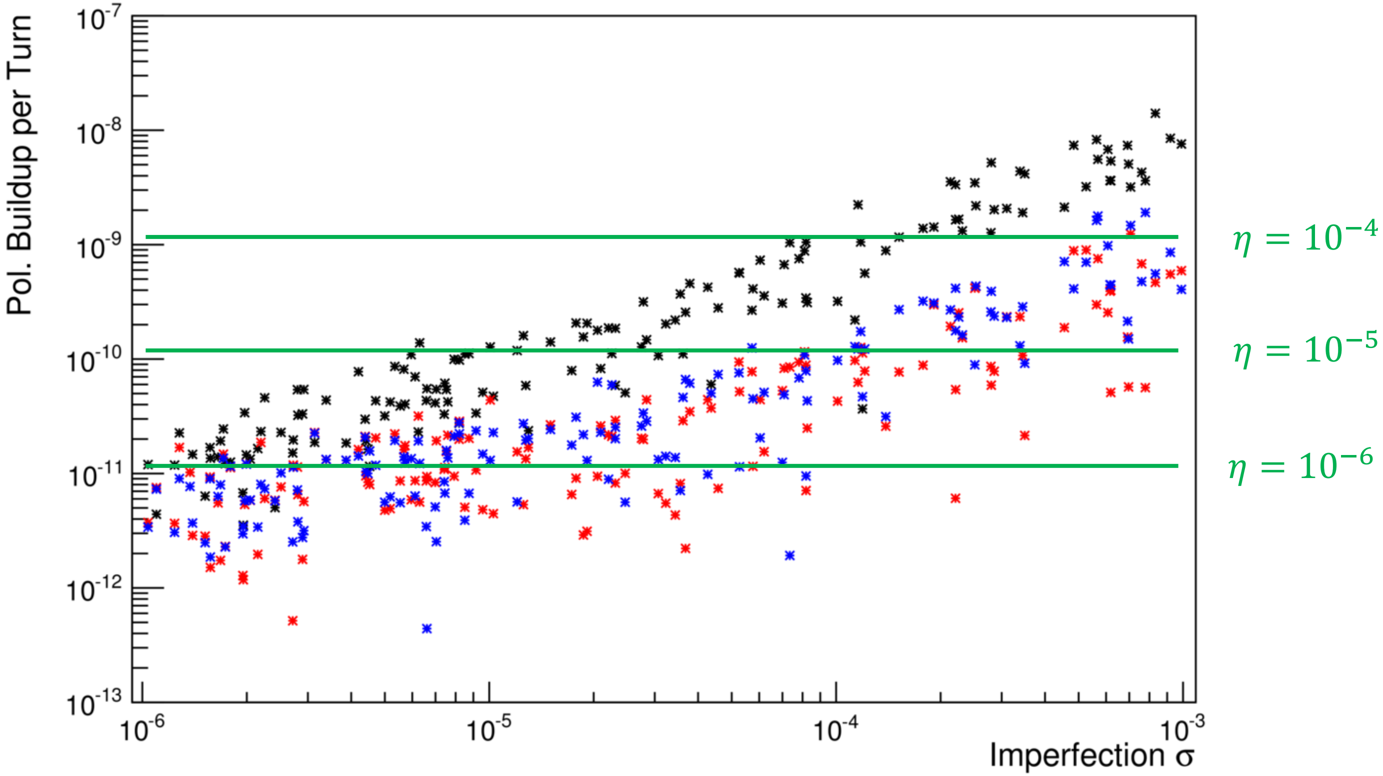
- Two orbit correction aims:
  1. Minimize orbit offsets at existing beam position monitors
  2. Minimize orbit offsets with respect to quadrupole centers



# Fake-EDM-signal for quadrupole shifts

- Existing correctors allow for reduction of about one order of magnitude



# Summary and Outlook

- Simulation framework successfully extended:
  - EDM contribution and radiofrequency fields.

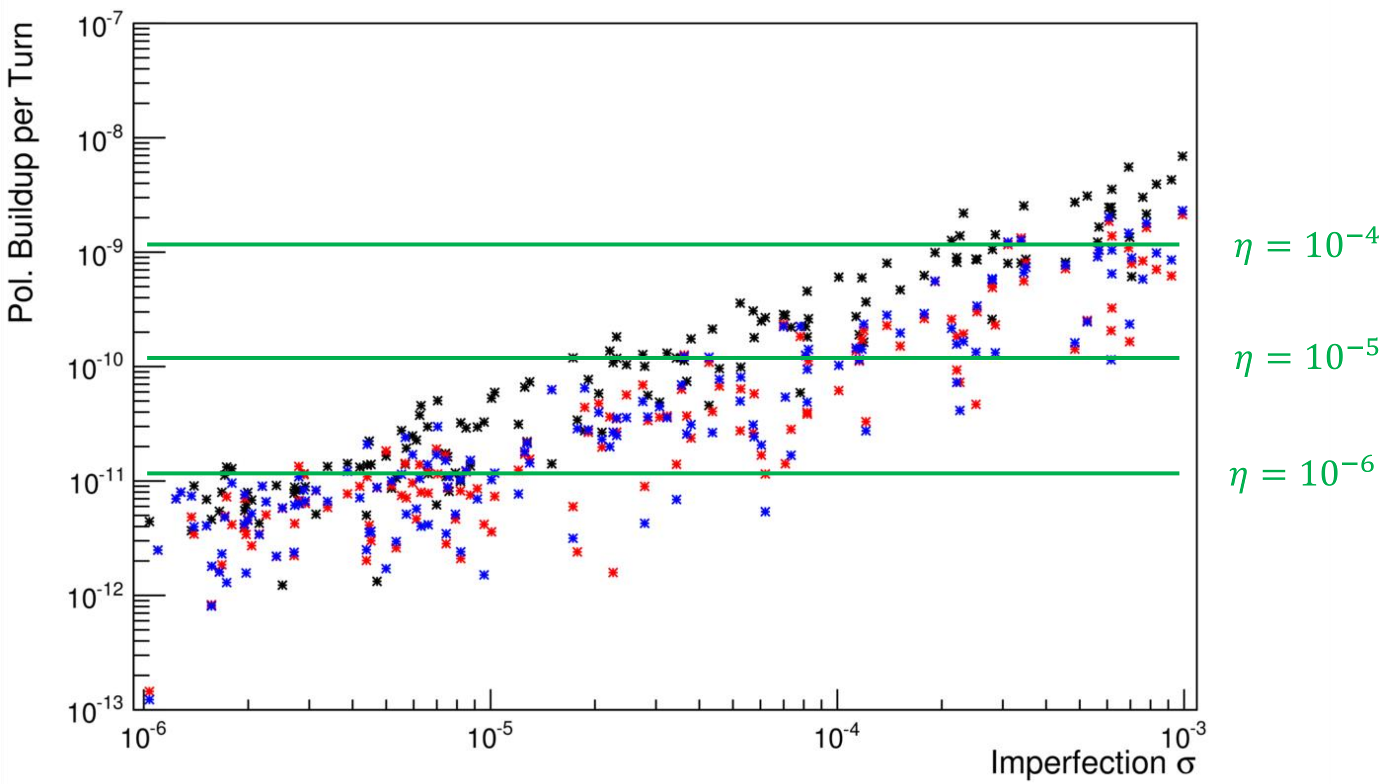
- Tough requirements for EDM measurements in pure magnetic rings:
  - Quadrupole shifts of $0.1\ \mathrm{mm}$:
    estimated systematic limit $\eta \approx 10^{-4} \rightarrow d \approx 5 \cdot 10^{-19} \mathrm{e\ cm}$

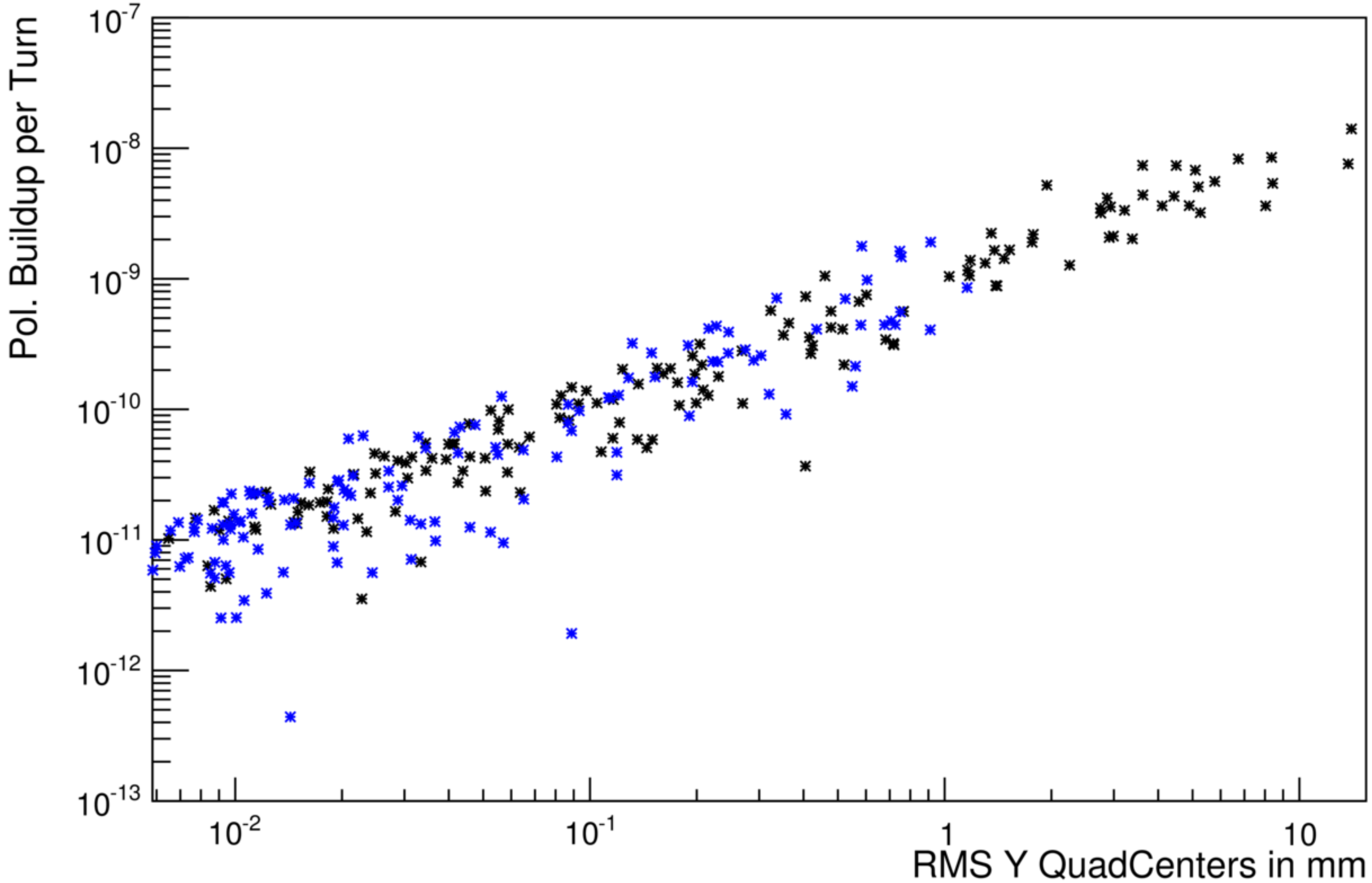
- Plans: Optimization of correction algorithm to take also spin motion into account
  - Idea: Correction of invariant spin axis tilt caused by imperfections
  - Preserve tilt caused by EDM
- Investigation of alignment options for the RF-ExB-Dipole itself
- Investigation of phase space motion

# SPARES

# Fake-EDM-signal for dipole rolls

- Two orbit correction aims:
  1. Minimize orbit offsets at existing beam position monitors
  2. Minimize orbit offsets with respect to quadrupole centers

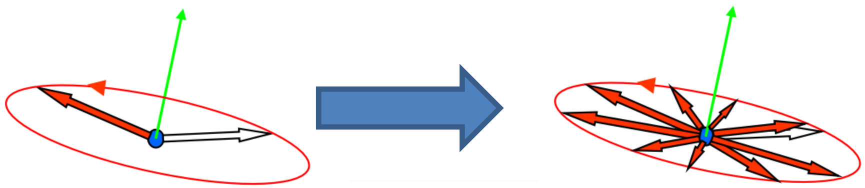




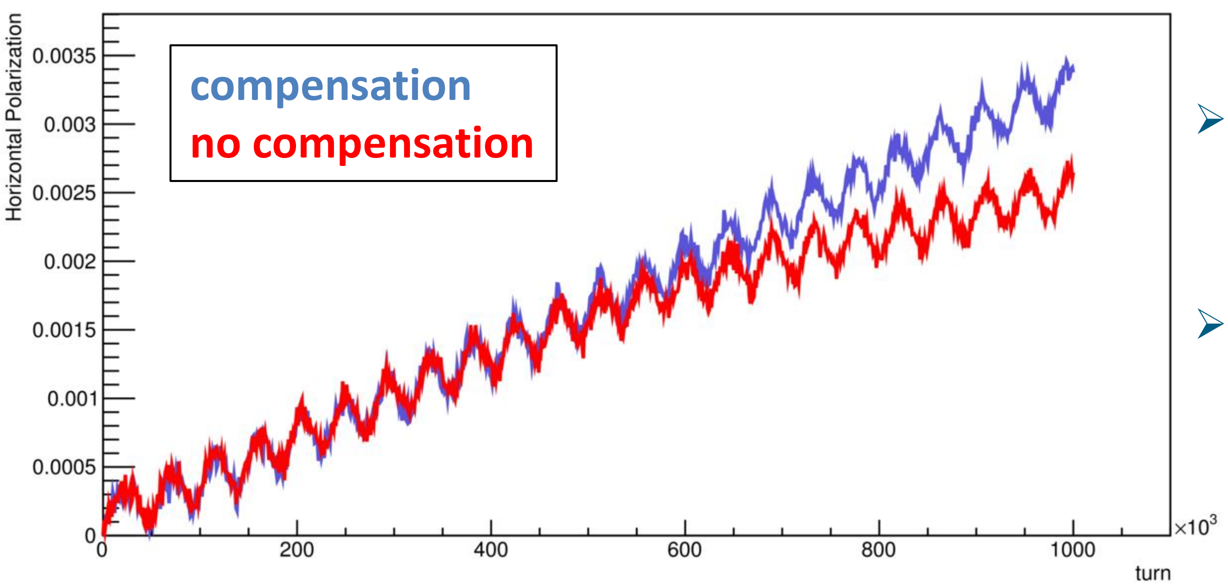
Pol. Buildup per Turn
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-2}$
$10^{-1}$
1
10
RMS Y QuadCenters in mm

# 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



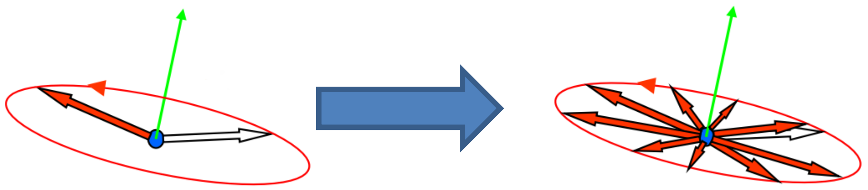
**Horizontal polarization vanishes!**




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

# 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

JÜLICH FORSCHUNGSZENTRUM

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

bunched

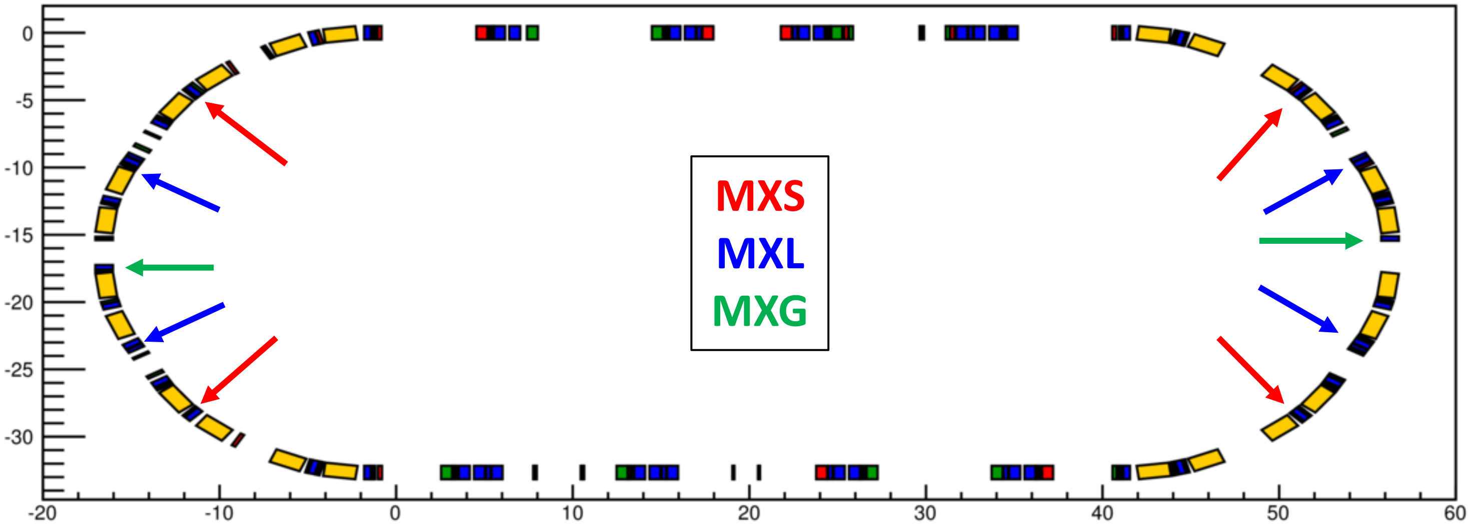
- Canceling energy deviations ($\nu_s = G\gamma$): $\left\langle\frac{\Delta\gamma}{\gamma_0}\right\rangle = 0$
  - $\frac{\Delta p}{p} \approx \frac{1}{\beta_0^2}\frac{\Delta\gamma}{\gamma_0} - \frac{1}{2\beta_0^4\gamma_0^2}\left(\frac{\Delta\gamma}{\gamma}\right)^2$
- Three conditions for $\left\langle\frac{\Delta\gamma}{\gamma_0}\right\rangle = 0$:
  - $\left\langle\left(\frac{\Delta L}{L_0}\right)_u\right\rangle = -\frac{\pi}{L_0}\cdot\epsilon_u\cdot\boldsymbol{\xi_u} = 0, \quad u \in \{x, y\}$
  - $\boldsymbol{\Delta} \equiv \left[\boldsymbol{\alpha_1} + \frac{3}{2\gamma_0^2}\left(\beta_0^2 - \left(\alpha_0 - \frac{1}{\gamma_0^2}\right)\right)\right] = 0$

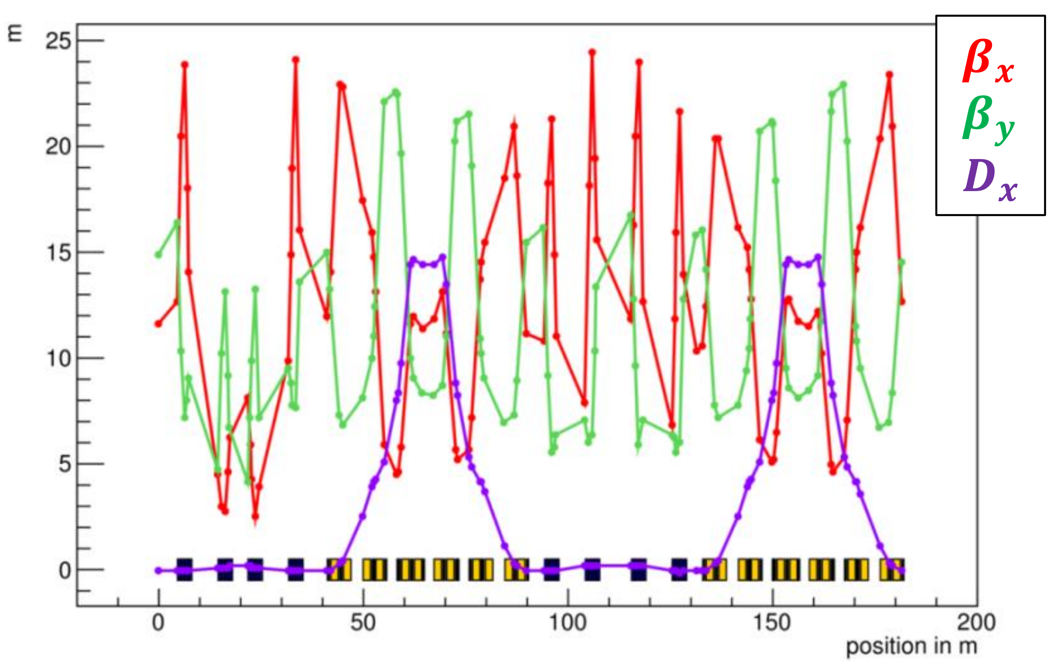
$$\epsilon_u = \frac{u_{max}^2}{\beta_u}$$

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

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

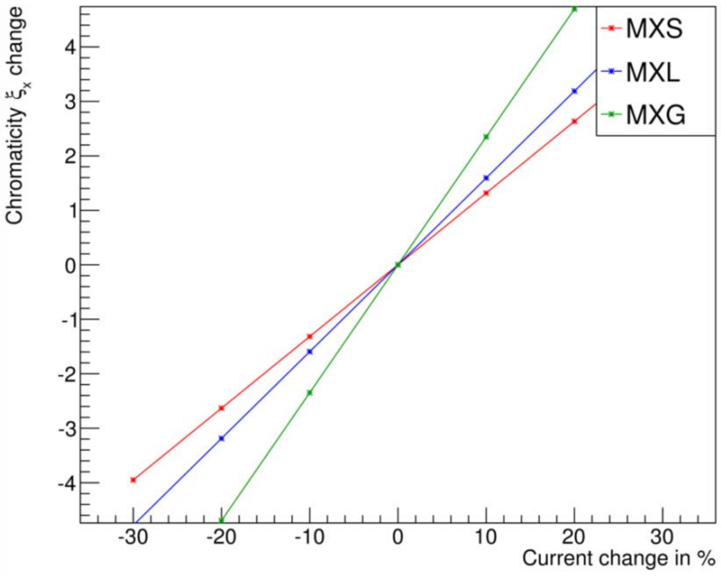
# Sextupoles at COSY

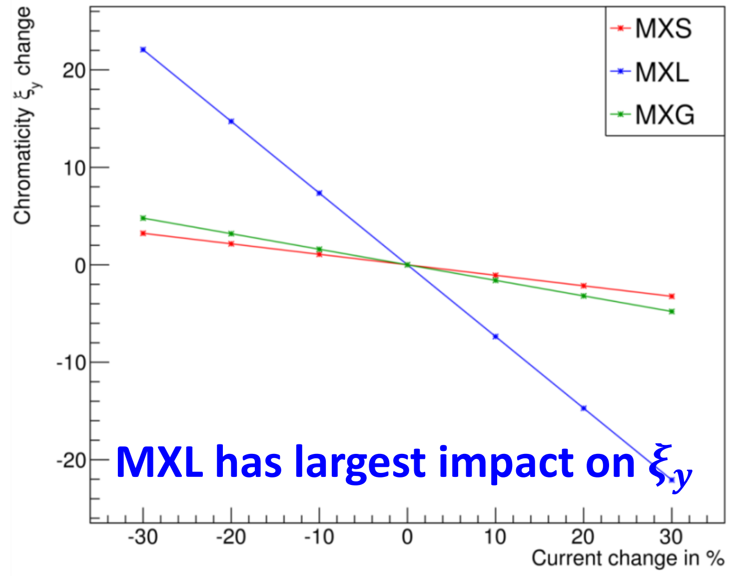


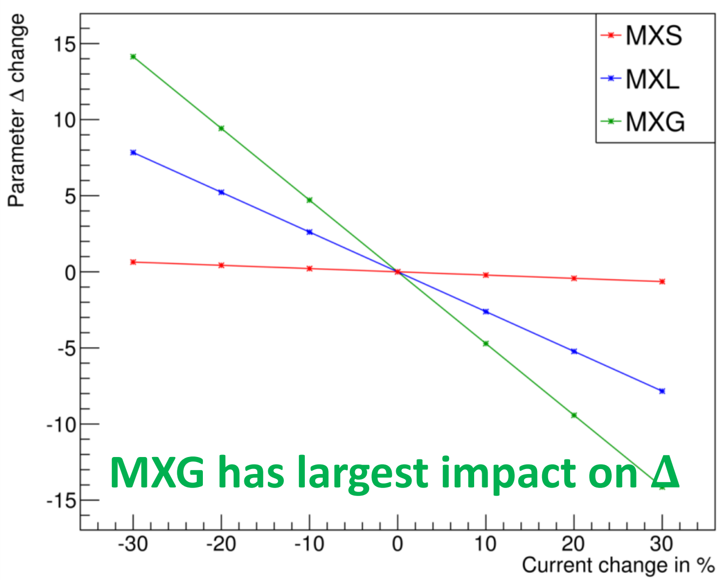




- Straights:
  - Minimized dispersion
- Arcs:
  - Large dispersion
  - 3 sextupole families

# Sextupoles at COSY



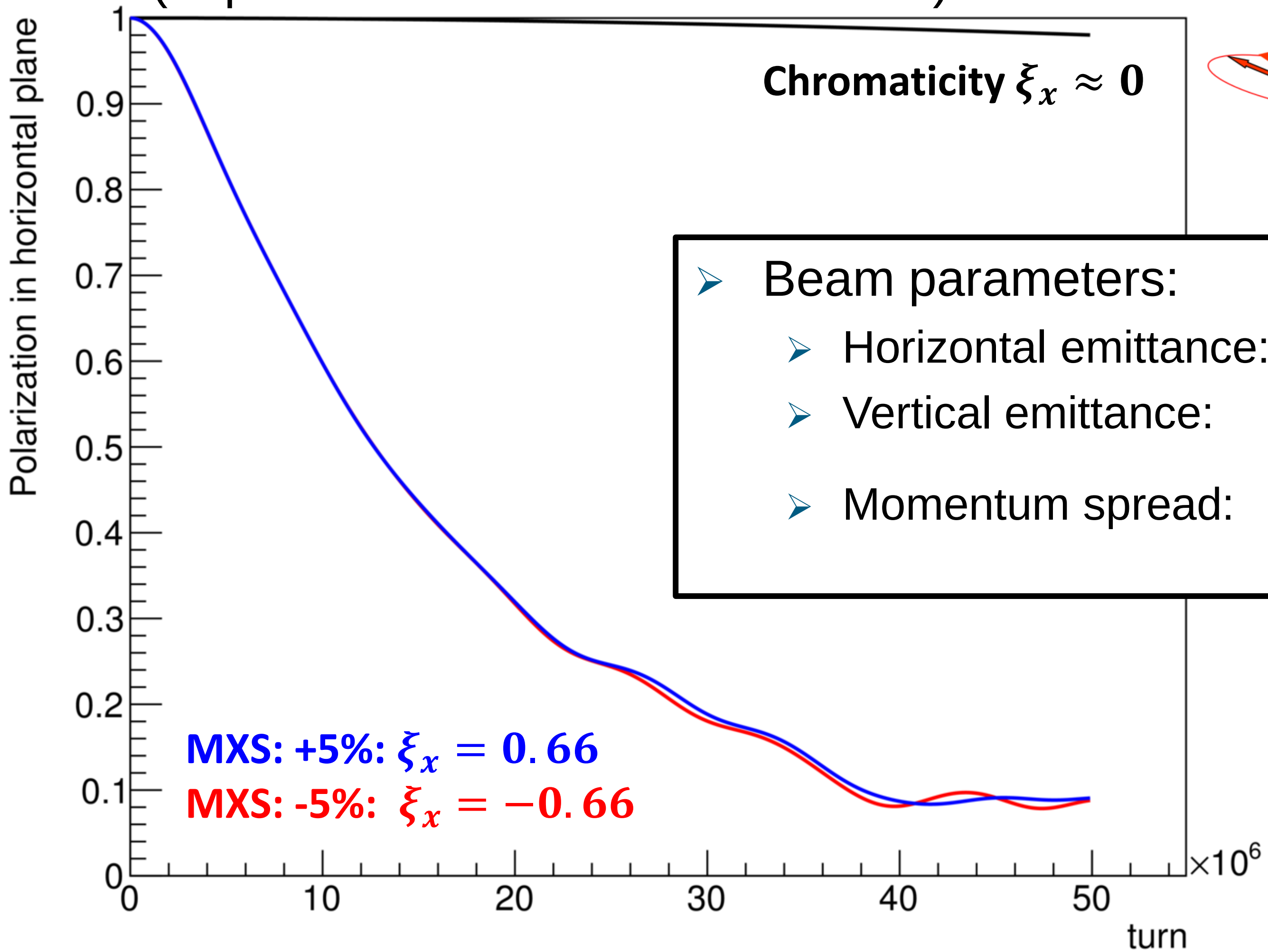



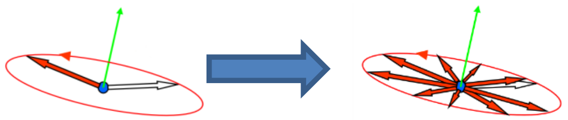

- Linear equation system to minimize $\xi_x, \xi_y$ and Δ at the same time

- MXL dominates $\xi_y$ change
- MXG dominates Δ change

# SCT Simulations

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



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

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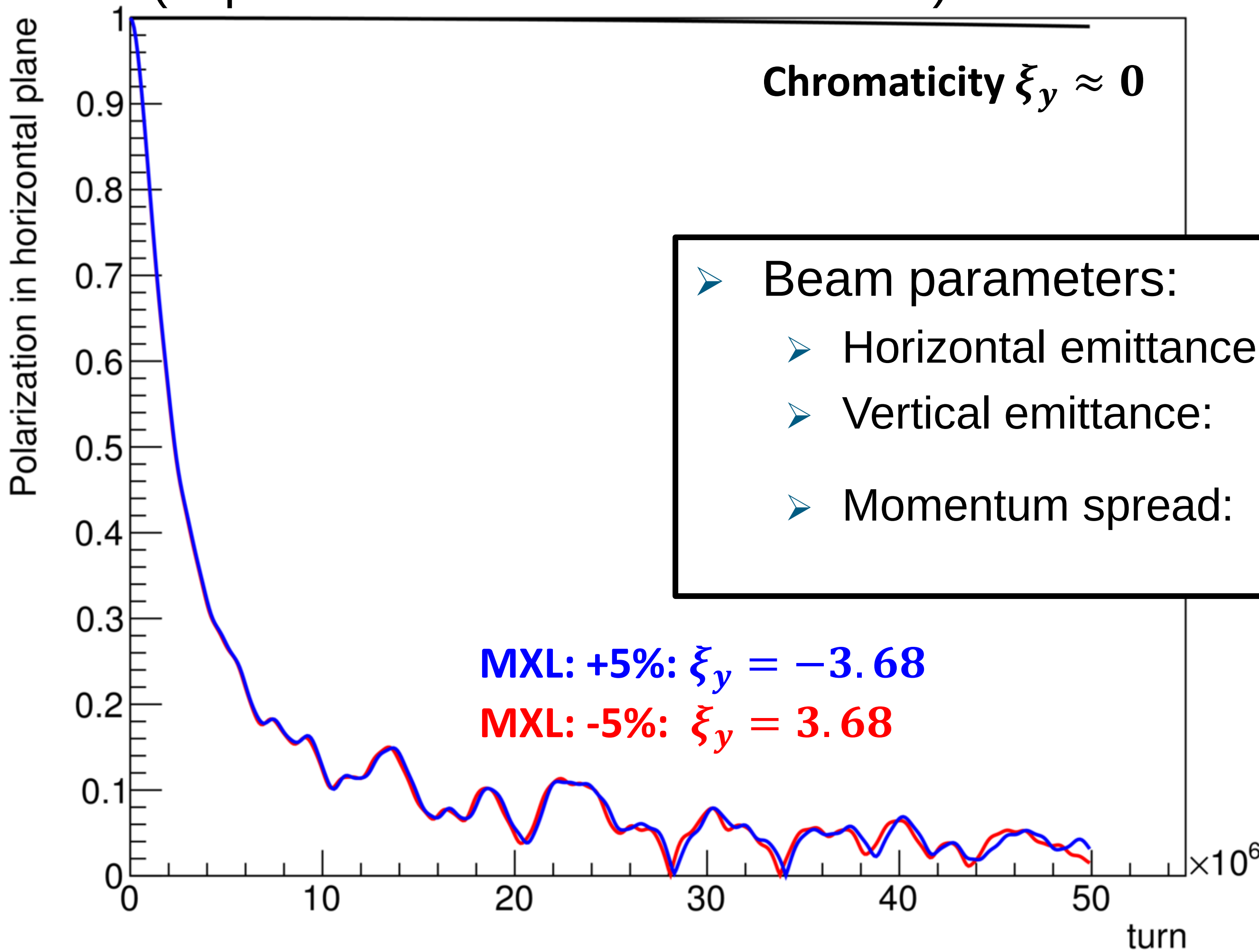



**Chromaticity $\xi_y \approx 0$**

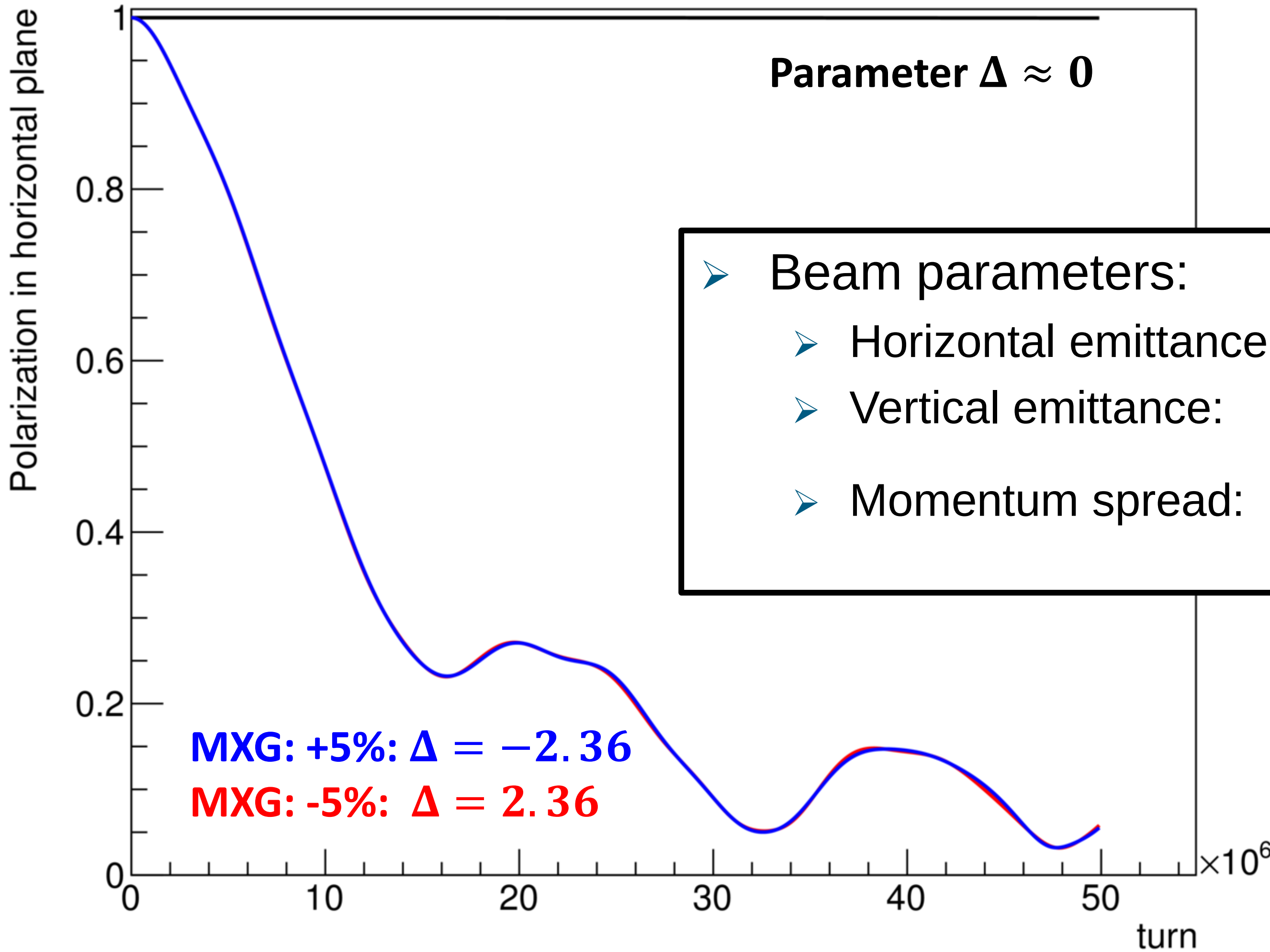
- Beam parameters:
  - Horizontal emittance: $\epsilon_x = 0\ \text{mm mrad}$
  - Vertical emittance: $\boldsymbol{\epsilon_y = 5\ \text{mm mrad}}$
  - Momentum spread: $\left(\frac{\Delta p}{p}\right)_{rms} = 0$

**MXL: +5%: $\xi_y = -3.68$**

**MXL: -5%: $\xi_y = 3.68$**

# SCT Simulations

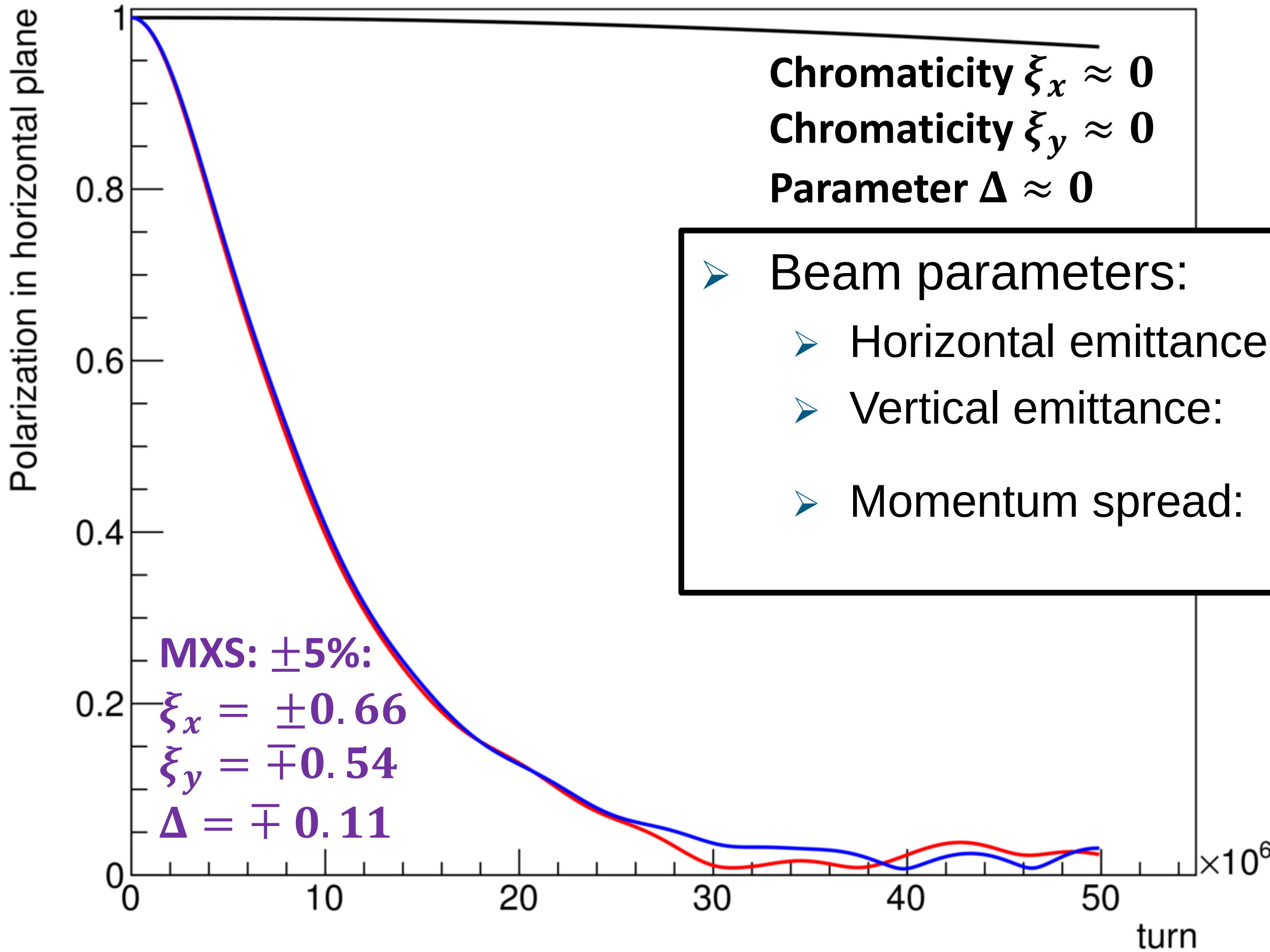
- Deuterons, $p = 970\ MeV/c$, initially radial polarized (→ precession around vertical axis )




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

# SCT Simulations

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




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