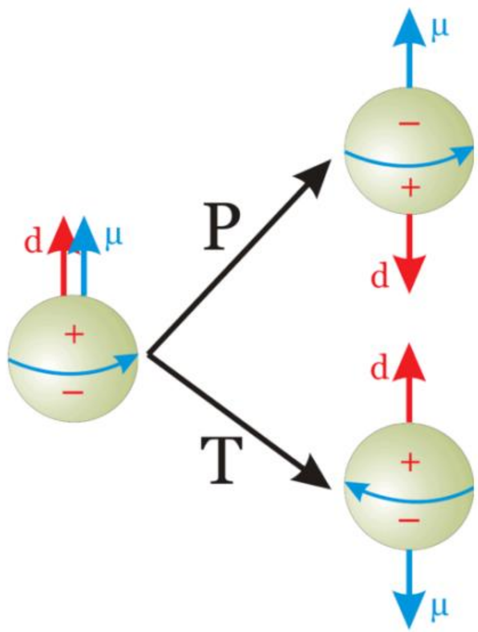
# Polarisation Lifetime Studies for EDM Measurements at COSY

2014-03-31 | Marcel Rosenthal on behalf of the JEDI Collaboration

# Outline

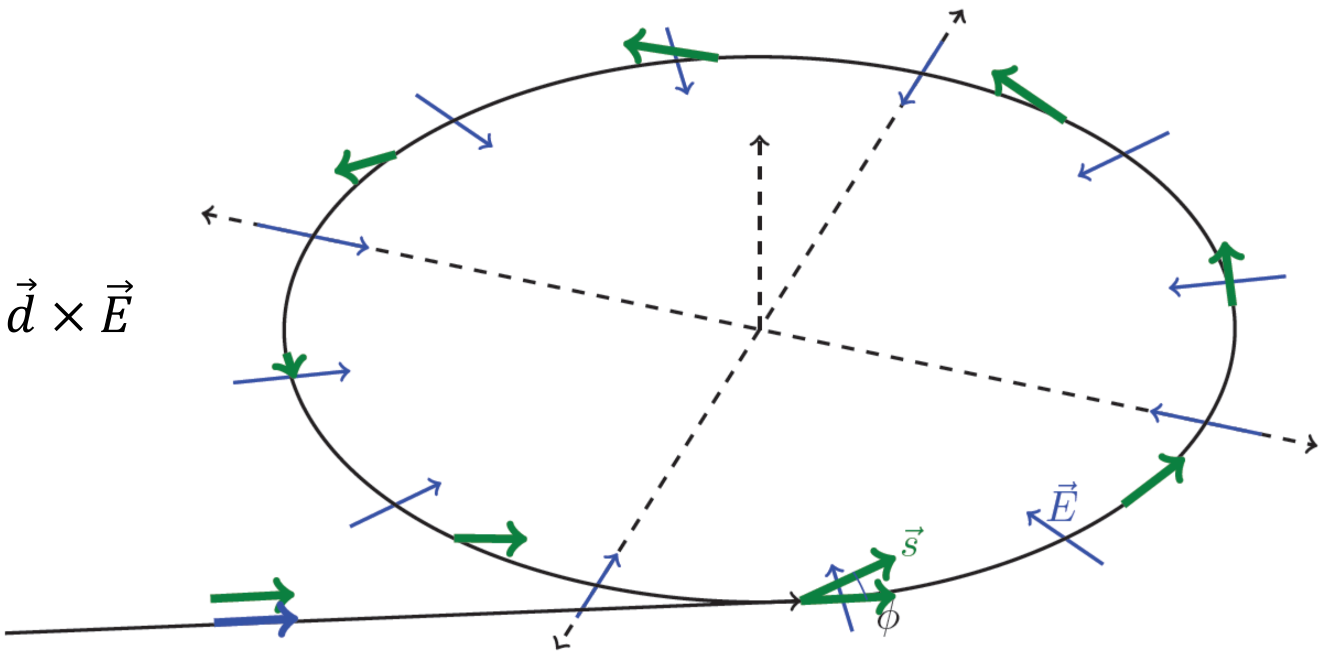
- What are **E**lectric **D**ipole **M**oments?
- Methods for EDM measurements in storage rings :
  - Dedicated pure electric ring
  - Existing conventional magnetic ring
- The Cooler Synchrotron COSY
- Spin Coherence Time studies at COSY

# 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




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

- 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

# 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

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

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

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

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

- „*Frozen Spin*“-Technique ($\vec{\Omega}_{MDM} = 0$):
  - pure electric ring: only works for $G > 0$

# Thomas-BMT-Equation

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

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

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

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

- *„Frozen Spin"*-Technique ($\vec{\Omega}_{MDM} = 0$):
  - pure electric ring: only works for $G > 0$
  - combined magnetic/electric ring: applicable for $G < 0$

# Thomas-BMT-Equation

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

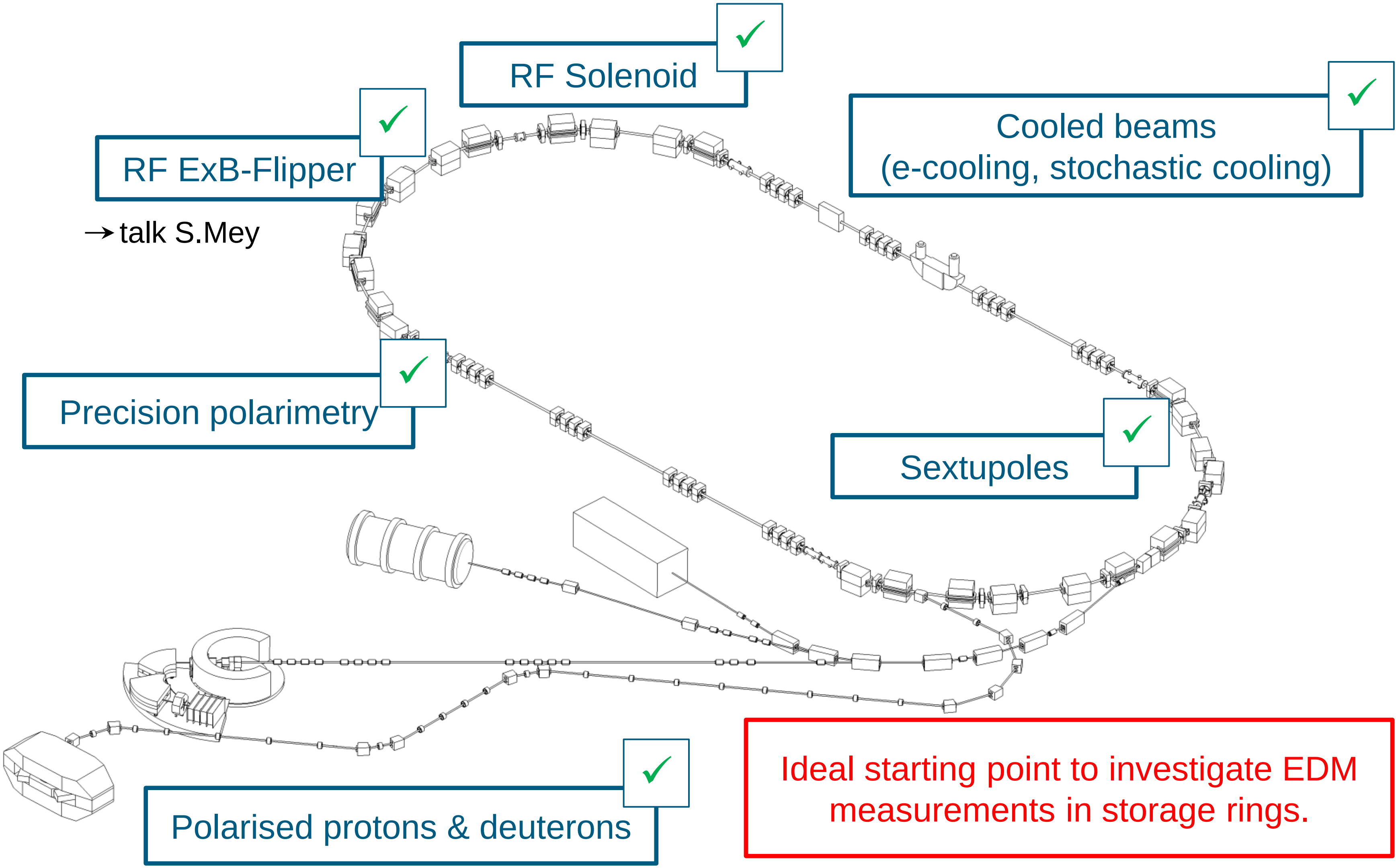
$$\frac{d\vec{S}}{dt} = \vec{S} \times \vec{\Omega}_{MDM} + \vec{S} \times \vec{\Omega}_{EDM}$$

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

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

- „*Frozen Spin*“-Technique ($\vec{\Omega}_{MDM} = 0$):
  - pure electric ring: only works for $G > 0$
  - combined magnetic/electric ring: applicable for $G < 0$
  - pure magnetic ring: technique not applicable ($\nu_s = G\gamma$)
    - Different principle for precursor measurements at COSY, Jülich needed

# The Cooler Synchrotron COSY




Ideal starting point to investigate EDM measurements in storage rings.

# Measurement Principle @ COSY

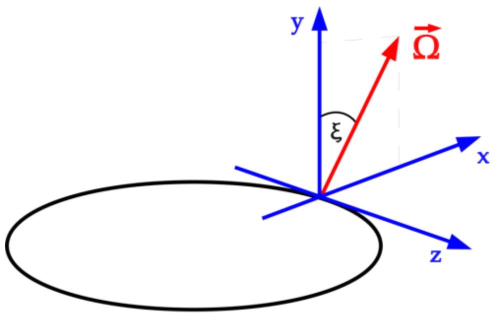
$$\tan\xi = \frac{\eta\beta}{2G}$$

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

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

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

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




- No net buildup of signal

# Measurement Principle @ COSY

JÜLICH FORSCHUNGSZENTRUM

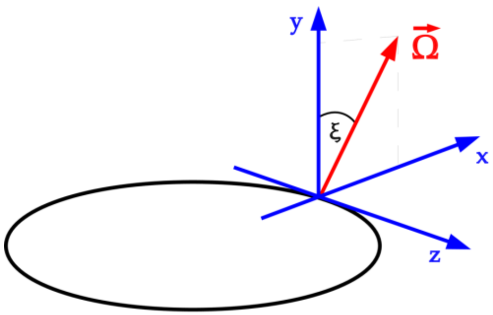
$$\tan\xi = \frac{\eta\beta}{2G}$$

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

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

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

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




- No net buildup of signal
- Idea: Induce EDM related spin resonance
  - 1. RF-E-Dipole

$$f_{RF} = |K + G\gamma|\cdot f_{rev}$$

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

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

Problem: transversal beam excitation!

# Measurement Principle @ COSY

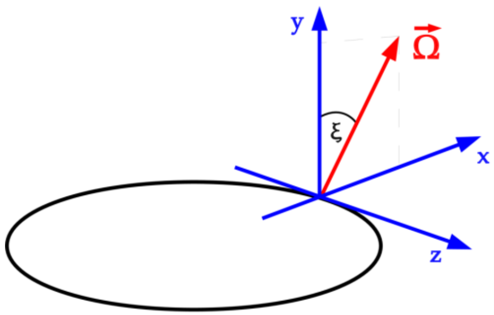
$$\tan\xi = \frac{\eta\beta}{2G}$$

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

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

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

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



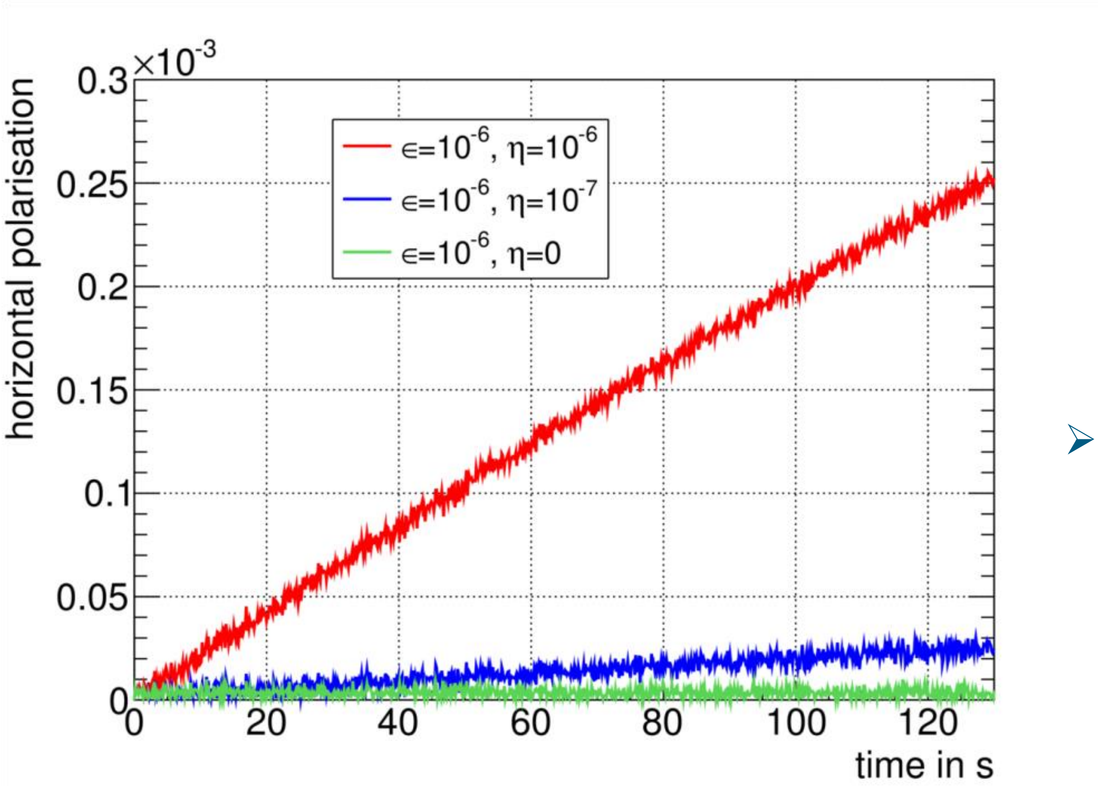

- No net buildup of signal
- Idea: Induce EDM related spin resonance
  - 2. RF-E×B-Dipole

$$f_{RF} = |K + G\gamma| \cdot f_{rev}$$

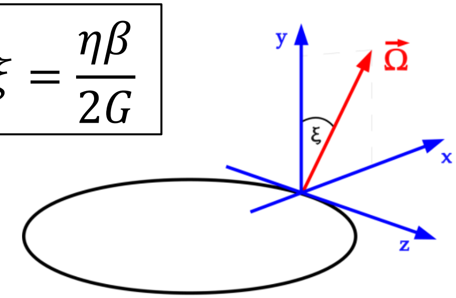
$$\vec{\Omega}_{MDM} = \frac{e}{\gamma m}\left[G\gamma\,\vec{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{E}\times\vec{\beta}}{c} - \frac{G\gamma^2}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{B})\right]$$

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

# EDM measurements @ COSY




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




- Buildup per revolution:

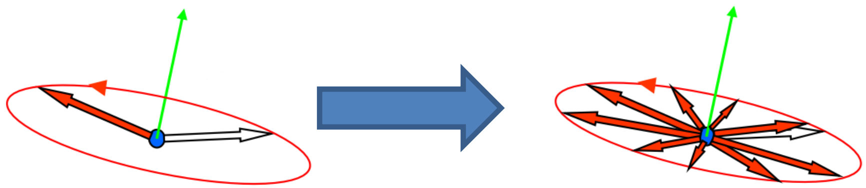
$$\Theta = \frac{\psi\xi}{2} = 4\pi \cdot \frac{\epsilon\xi}{2}$$

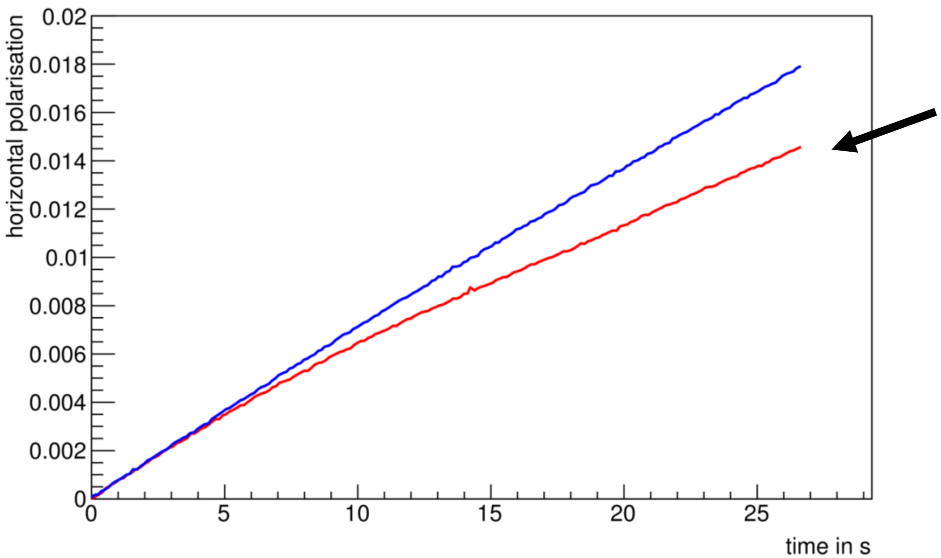
Deuterons:

| 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 | $10^{-9}$ | $10^{-12}$ |

# 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

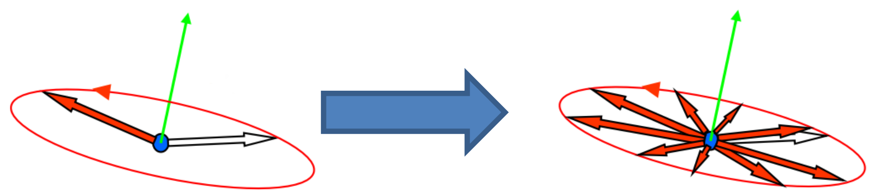





- Buildup limited by Spin Coherence Time
- Decoherence has to be minimized

# 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



- 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:
  - $\frac{\Delta L}{L_0} = \left(\frac{\Delta L}{L_0}\right)_x + \left(\frac{\Delta L}{L_0}\right)_y + \left(\frac{\Delta L}{L_0}\right)_{\frac{\Delta p}{p}}$
  - $\left(\frac{\Delta L}{L_0}\right)_{\frac{\Delta p}{p}} = \alpha_0 \cdot \frac{\Delta p}{p} + \alpha_1 \cdot \left(\frac{\Delta p}{p}\right)^2$

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

# Spin Coherence Time II

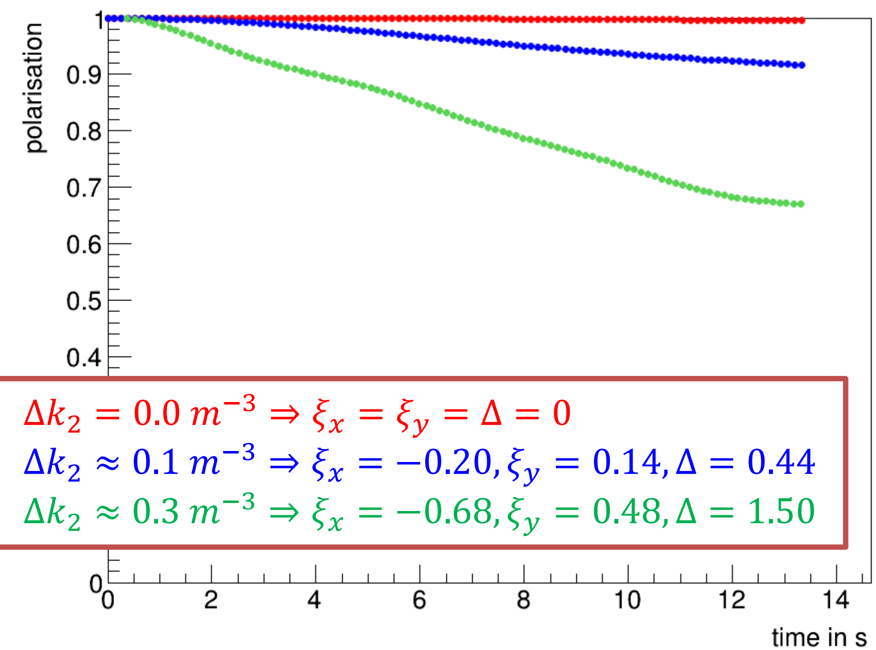
JÜLICH FORSCHUNGSZENTRUM

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

$$\left\langle \left(\frac{\Delta L}{L_0}\right)_u \right\rangle = -\frac{\pi}{L_0} \cdot \epsilon_u \cdot \xi_u$$

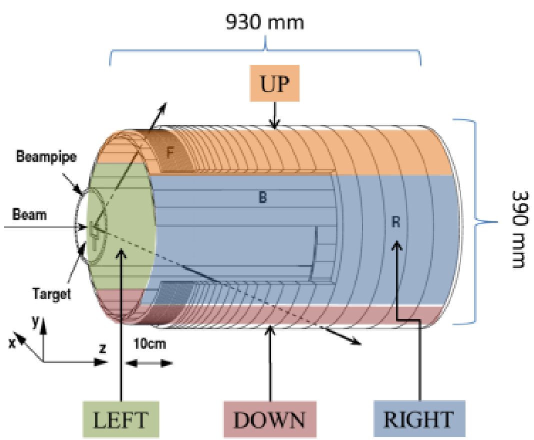
- Canceling energy deviations ($\nu_s = G\gamma$): $\left\langle \frac{\Delta \gamma}{\gamma_0} \right\rangle = 0$
  - $\left\langle \left(\frac{\Delta L}{L_0}\right)_x \right\rangle = \left\langle \left(\frac{\Delta L}{L_0}\right)_y \right\rangle = 0$
  - $\Delta = \left[\alpha_1 + \frac{3}{2\gamma_0^2}\left(\beta_0^2 - \left(\alpha_0 - \frac{1}{\gamma_0^2}\right)\right)\right] = 0$

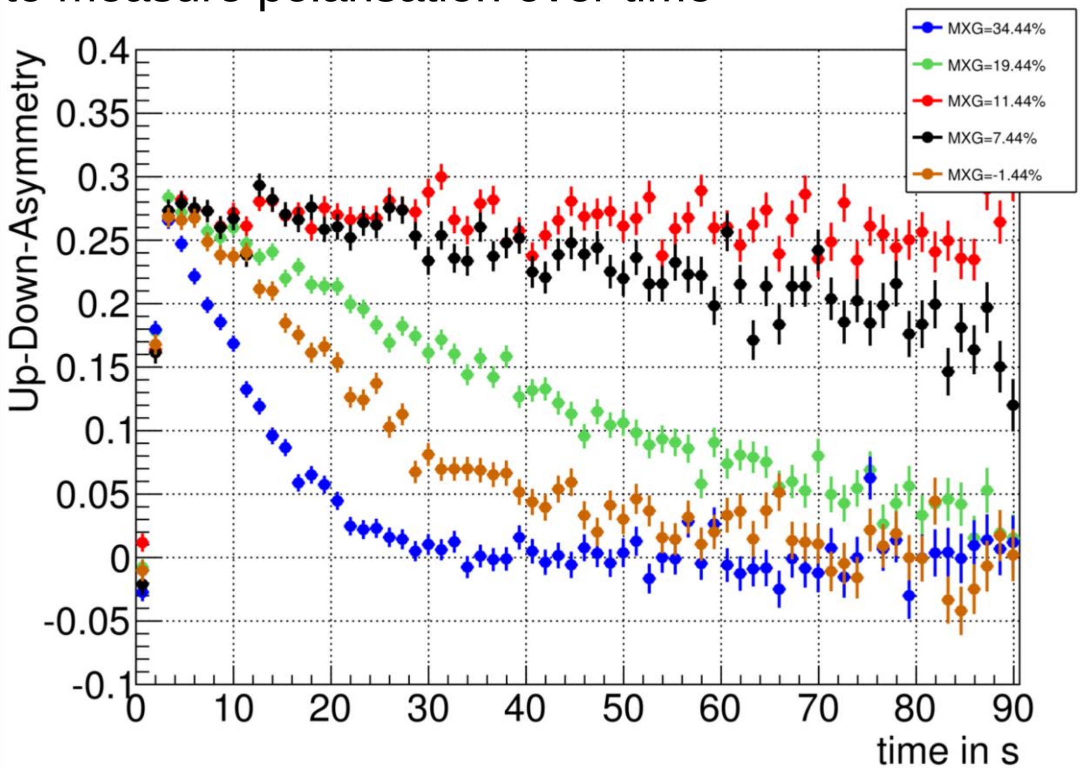
- Vary sextupoles to manipulate $\xi_x,\ \xi_y,\ \Delta$



# Spin Coherence Time III

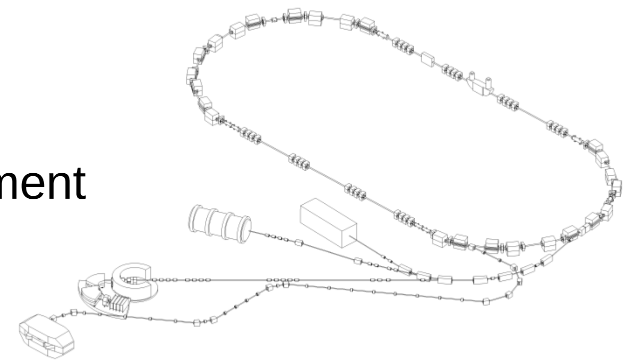
- SCT studies performed during last beam time:
  - Polarised deuterons @ 970 MeV/c
  - Electron-cooled
  - „Heated“ in 1 direction (horizontally or longitudinally)
  - Beam steered on target to measure polarisation over time



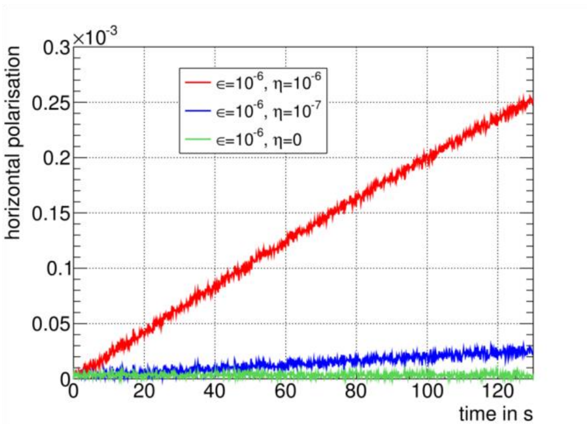




- Polarisation evolution for different sextupole configurations

# Summary & Outlook

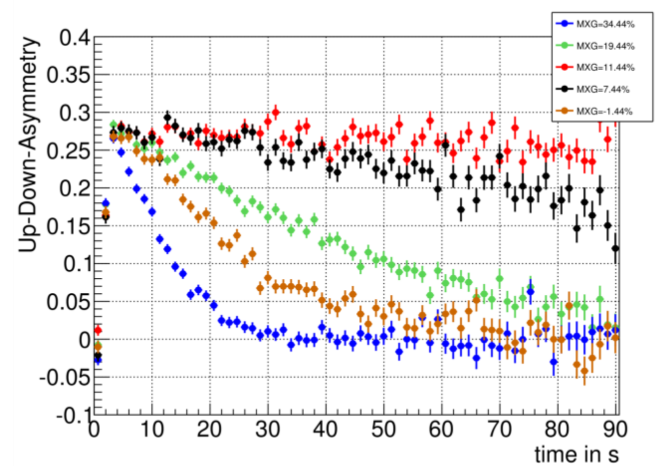


- EDM measurements in storage rings
  - Feasibility studies and precursor experiment at COSY/Jülich




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

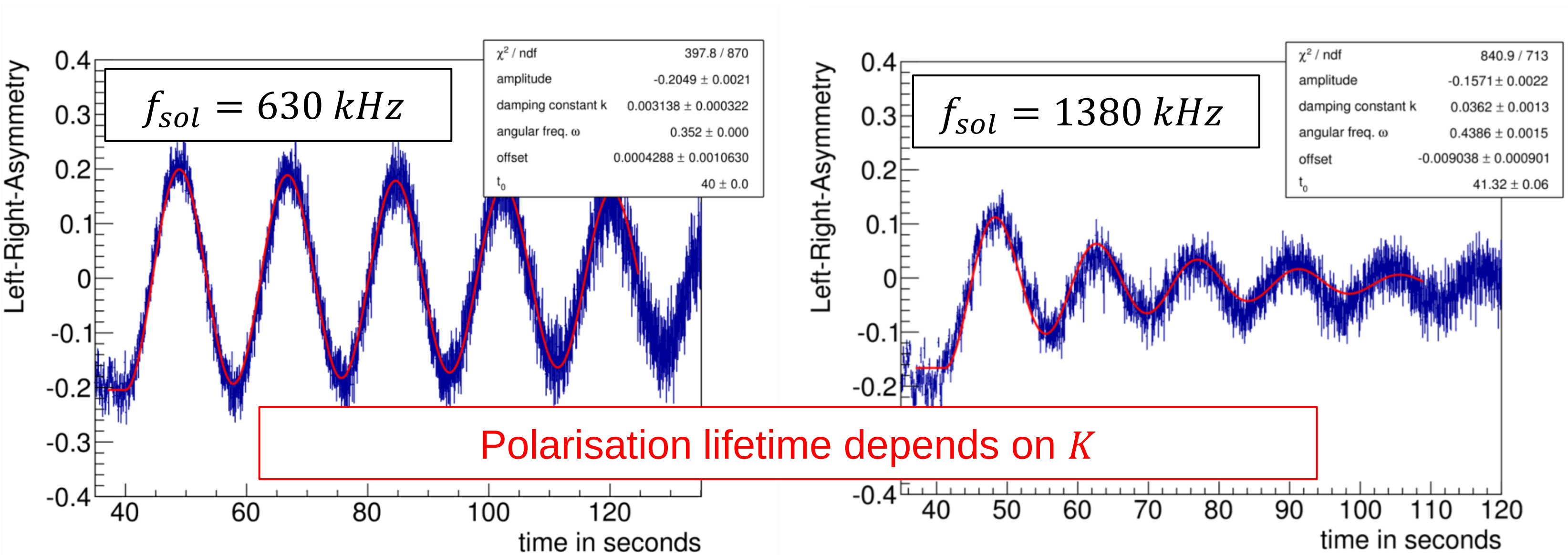
- Preservation of polarisation mandatory
  - Sextupole corrections
- *Outlook: further investigation of SCT*



# Spares

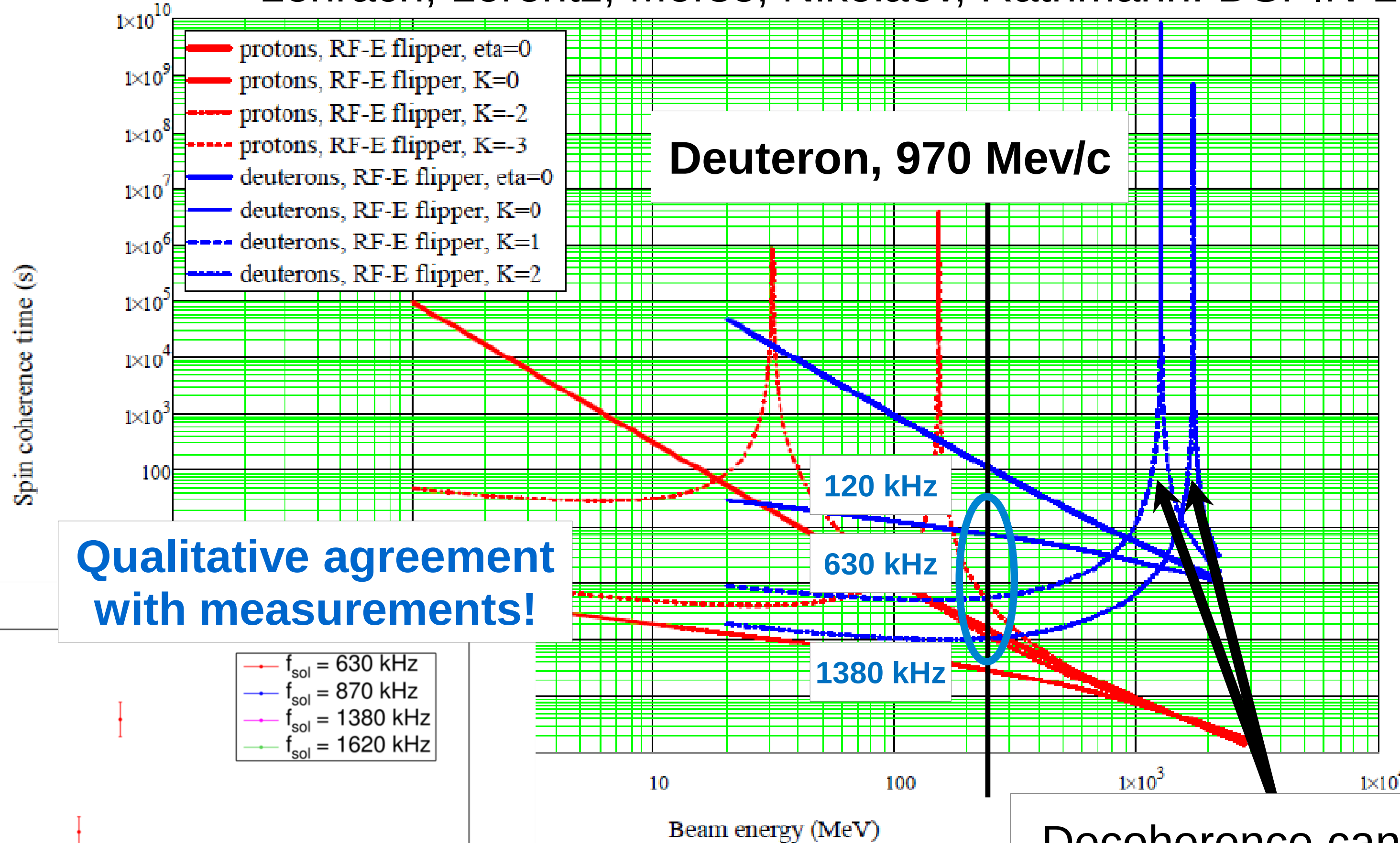
# RF Induced Spin Resonances

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

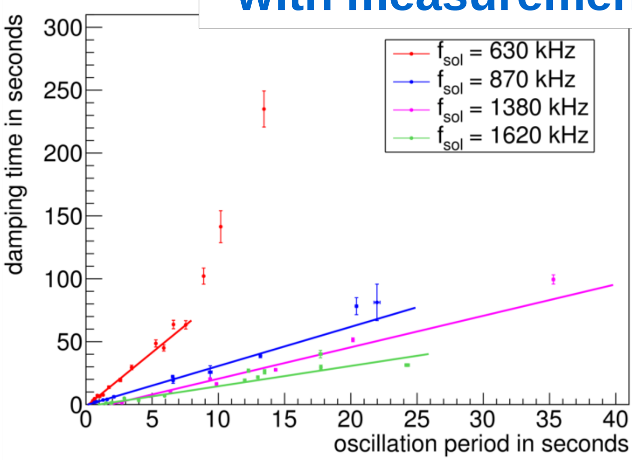


# Theoretical prediction

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



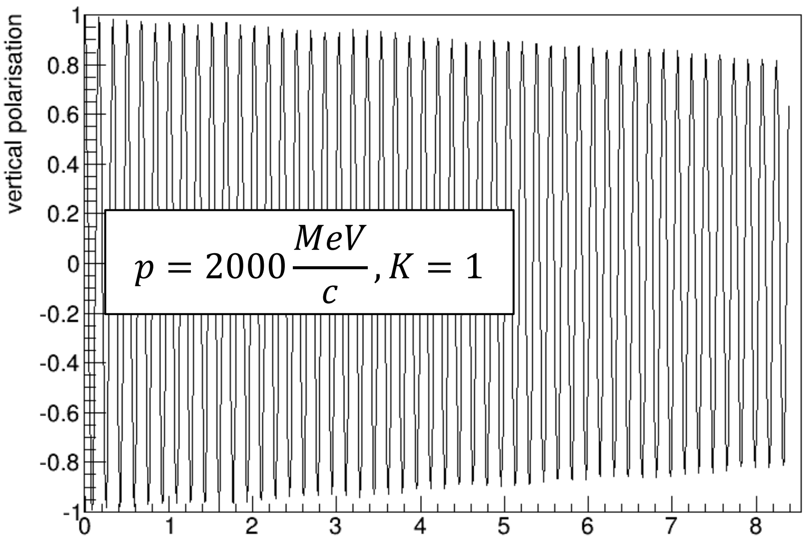

**Qualitative agreement with measurements!**

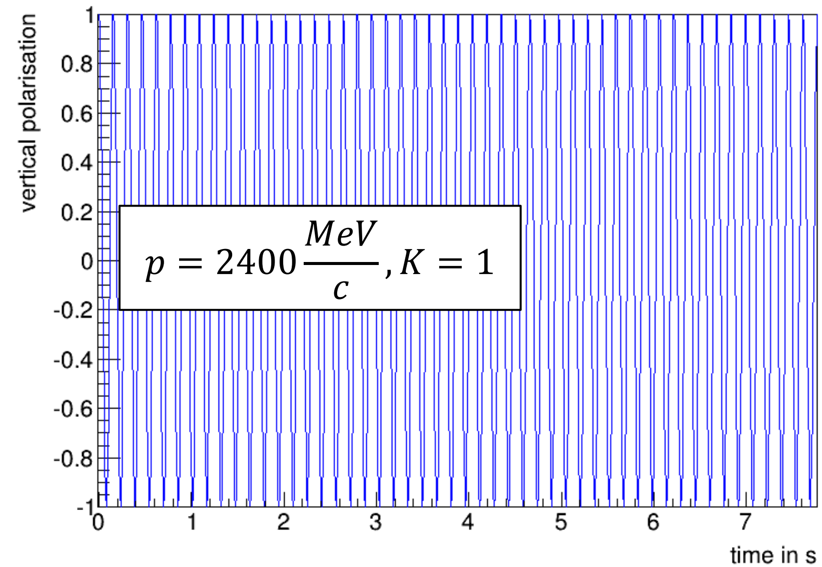


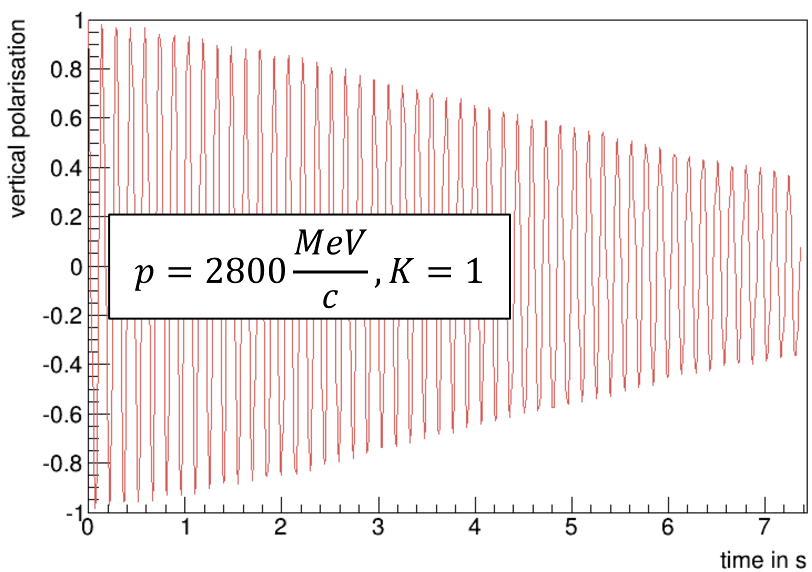

Decoherence cancelled for

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

# 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.

# Statistical Sensitivity for electric/combined-ring

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

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

$\Rightarrow \sigma \approx 10^{-29}\, e{\cdot}$cm/year (for magnetic ring $\approx 10^{-24}\, e{\cdot}$cm/year)
Expected signal $\approx$ 3nrad/s (for $d = 10^{-29}\, e{\cdot}$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 | |
| $\gamma$ | relativistic factor | 1.13 |
| | $p = 1$GeV/$c$ | |
| $U$ | circumference of COSY | 180 m |
| $E \cdot L$ | integrated electric field | $0.1 \cdot 10^6$ V |
| $N$ | nb. of stored particles/cycle | $2 \cdot 10^9$ |

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

JÜLICH
FORSCHUNGSZENTRUM

# 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 $d = 10^{-29} e{\cdot}\text{cm}$ 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 $B_r$