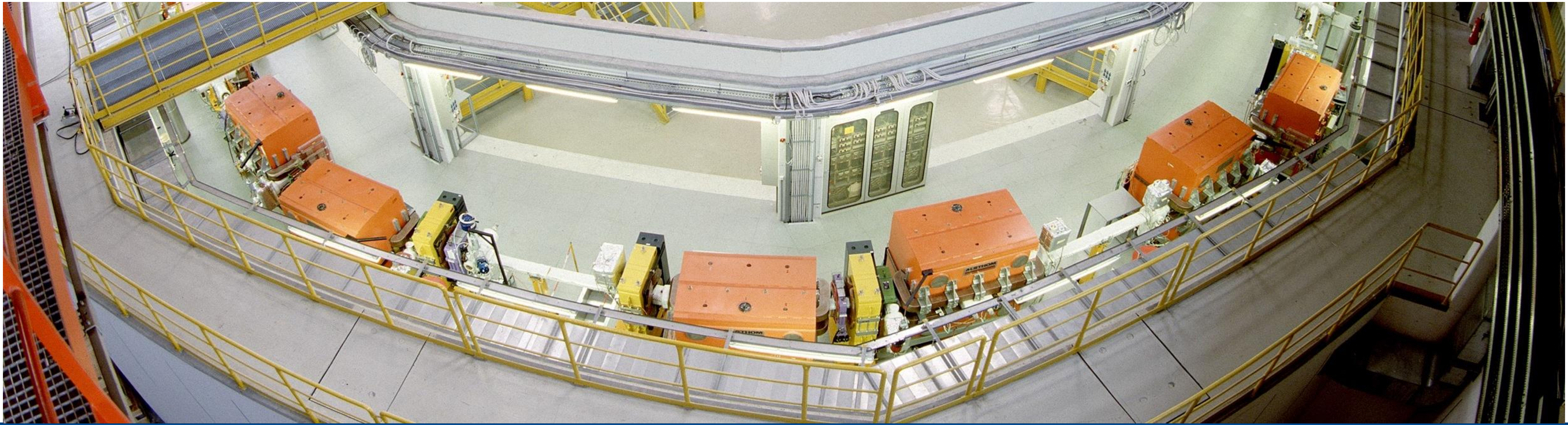

STATIC AND OSCILLATING ELECTRIC DIPOLE MOMENT SEARCHES OF CHARGED PARTICLES IN STORAGE RINGS

STORI‘24 HUIZHOU, CHINA

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OUTLINE

- Motivation: Electric Dipole Moments and Axions / ALPs searches
- Measurement principles & experimental techniques
- Experiments Results: on static and oscillating EDMs
- Staged approach toward dedicated EDM ring
- Summary

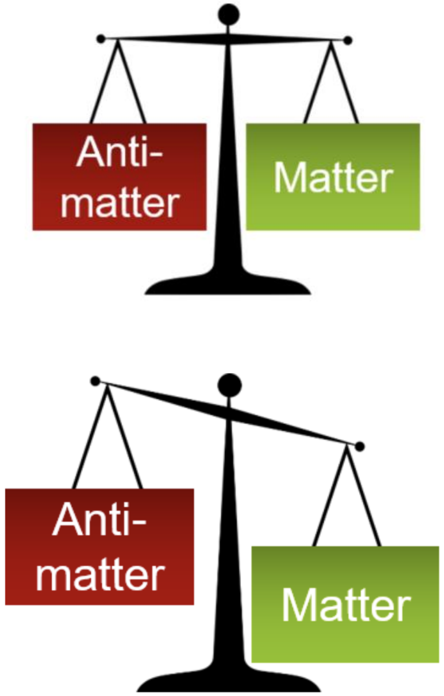
MATTER ANTIMATTER ASYMMETRY

- Predominance of matter over antimatter in the Universe

- Baryon Asymmetry：

Baryon-to-photon ratio	
Observation	10^{-10}
Theory (SMC)	10^{-18}

According to A. Sakharov: CP Violation is needed.



ELECTRIC DIPOLE MOMENT (EDM)

- EDM : permanent separation of + and – charges.
- Fundamental property of elementary particles.

$$\vec{d} = d \cdot \vec{s}$$

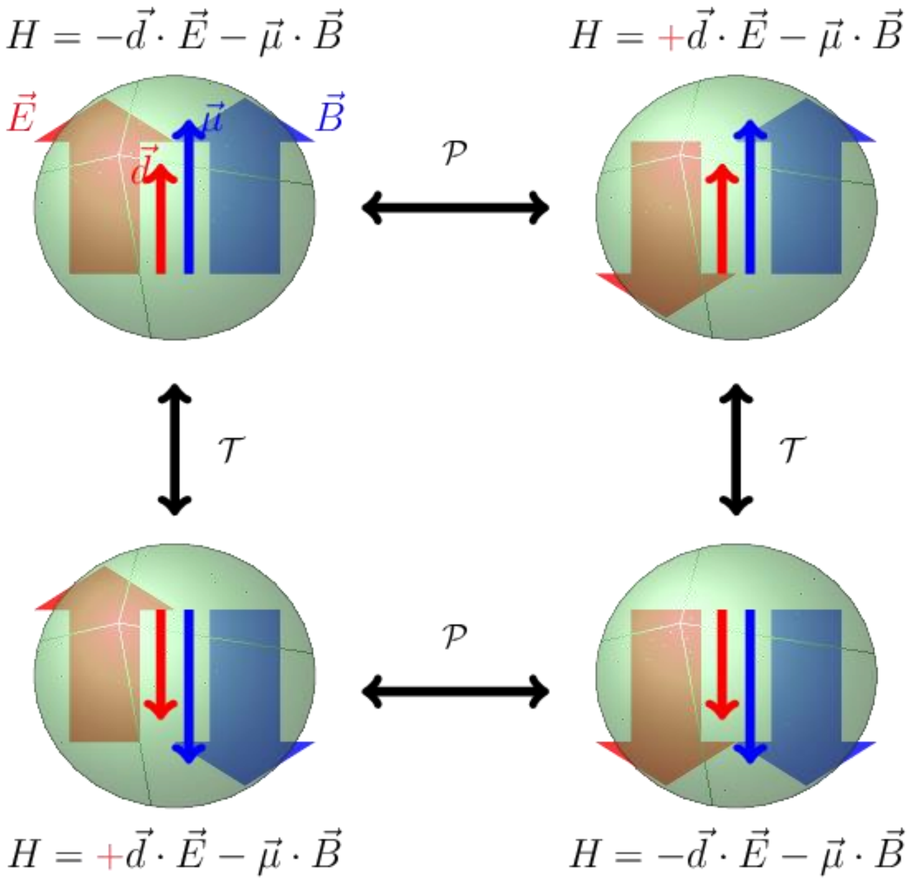
- Hamiltonian:

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

$$P(H) = +\vec{d} \cdot \vec{E} - \vec{\mu} \cdot \vec{B}$$

$$T(H) = +\vec{d} \cdot \vec{E} - \vec{\mu} \cdot \vec{B}$$

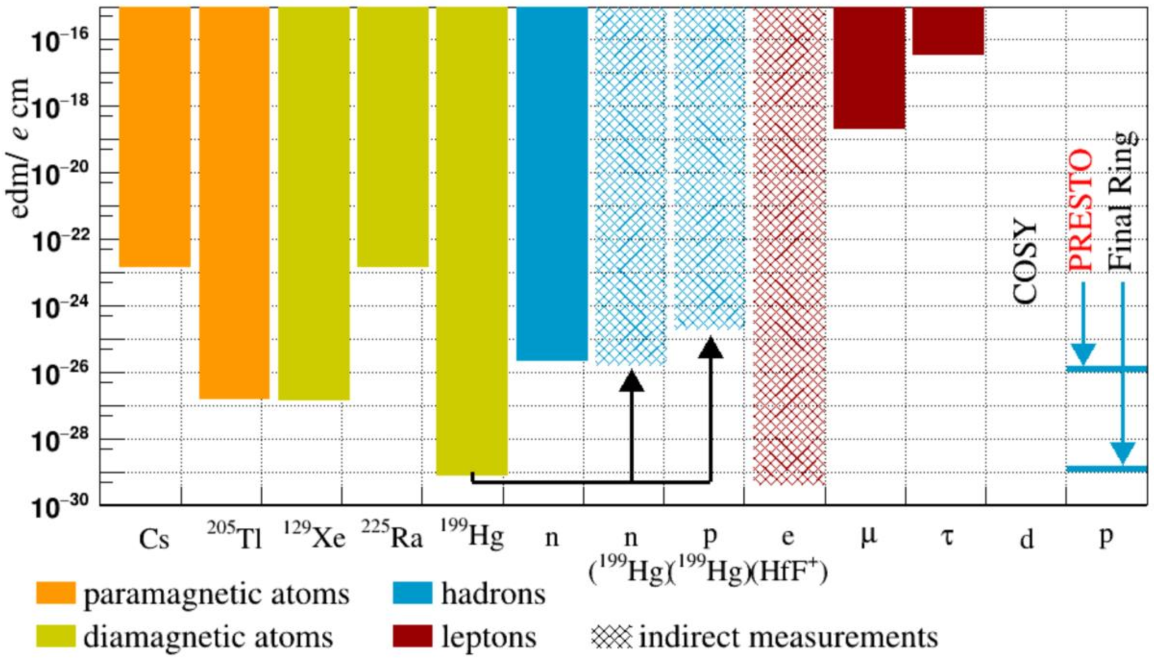
- According to CPT Theorem: T Violation = CP Violation



EDM violates both P and CP symmetry

EDM LIMITS

- No direct measurements of electron and proton EDMs.
- No measurement of deuteron EDM.
- Higher sensitivity for charged hadrons (compared to neutrons)
  - longer lifetime
  - more stored polarized hadrons
  - can apply larger electric fields



SPIN PRECESSION IN STORAGE RINGS

- Thomas-BMT Equation:

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m}\Big[\underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}}_{\vec{\Omega}_{MDM}} + \underbrace{\frac{\eta}{2}(\vec{E} + \vec{v} \times \vec{B})}_{\vec{\Omega}_{EDM}}\Big] \times \vec{S}$$

- magnetic dipole moment (MDM): $\vec{\mu} = 2(G+1)\frac{q\hbar}{2m}\vec{s}$
- electric dipole moment (EDM): $\vec{d} = \eta\frac{q\hbar}{2mc}\vec{s}$
- note: $\eta = 2 \cdot 10^{-15}$ for d = 10^{-29} $e\ cm$

$G = \frac{g-2}{2}$. $G \approx 1.79$ for proton, $G \approx -0.14$ for deuteron

Ω: angular precession frequency
G: anomalous magnetic moment

FROZEN SPIN

- Thomas-BMT Equation:

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m}\left[\underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}}_{\vec{\Omega}_{MDM}} + \underbrace{\frac{\eta}{2}(\vec{E} + \vec{v} \times \vec{B})}_{\vec{\Omega}_{EDM}}\right] \times \vec{S}$$

- Frozen spin: $\vec{\Omega}_{MDM} = 0$ (momentum and spin stay aligned)

➢ pure electric field for proton ($G > 0$): $G = \frac{1}{\gamma^2 - 1}$

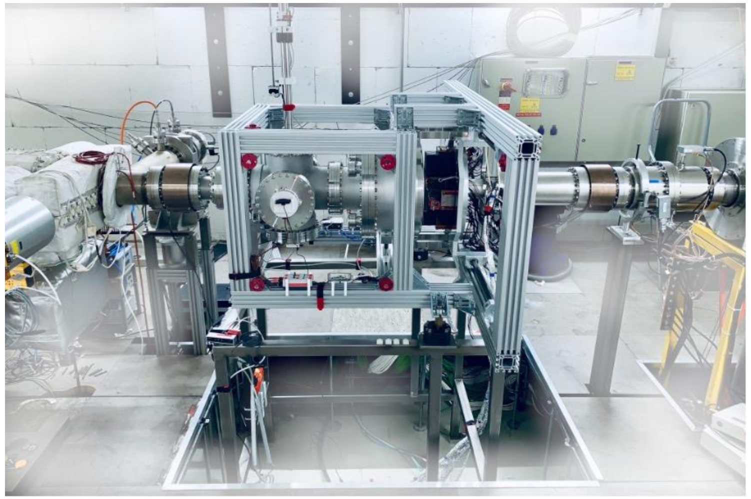
➢ special combination of E, B fields and γ for deuteron ($G < 0$)

→ $\vec{E}$ field causes the spin to precess out of the plane

Ω: angular precession frequency
G: anomalous magnetic moment

MEASUREMENT OF EDM IN STORAGE RING

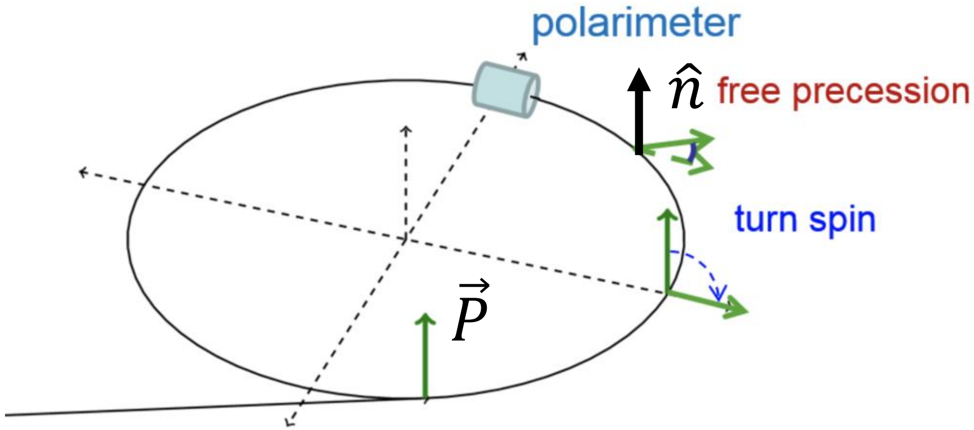
- Injection of vertically polarized deuteron beam.
- Flip spin into horizontal plane with solenoid.
- Search for time development of vertical polarization.



- Determination of Beam Polarization:

Vertical Polarization: Left – Right Asymmetry

Horizontal Polarization: Up – Down Asymmetry

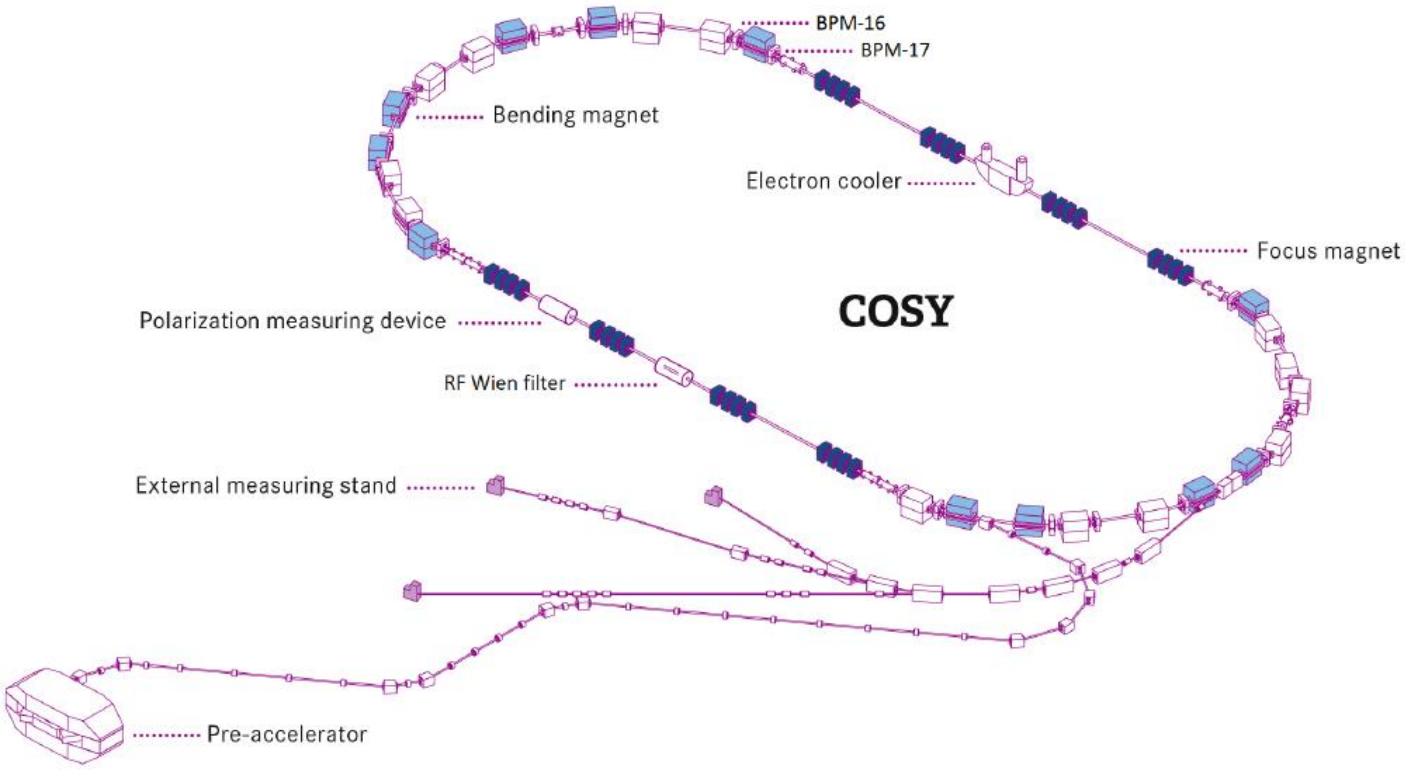


COoler SYnchrotron COSY

- Circumference: 184 m
- Polarized protons and deuterons
- Momenta: p = 0.3 - 3.7 GeV/c
- Selected working conditions:

  Deuteron beam,

  p = 0.97 GeV/c, T = 238 MeV
- Beam cooling



After 30 years of operation COSY has been closed in 2023.

SPIN COHERENCE TIME (SCT)

- Spin Coherence Time (SCT):

  time after total polarization drops to 1/e.

Depolarization source:

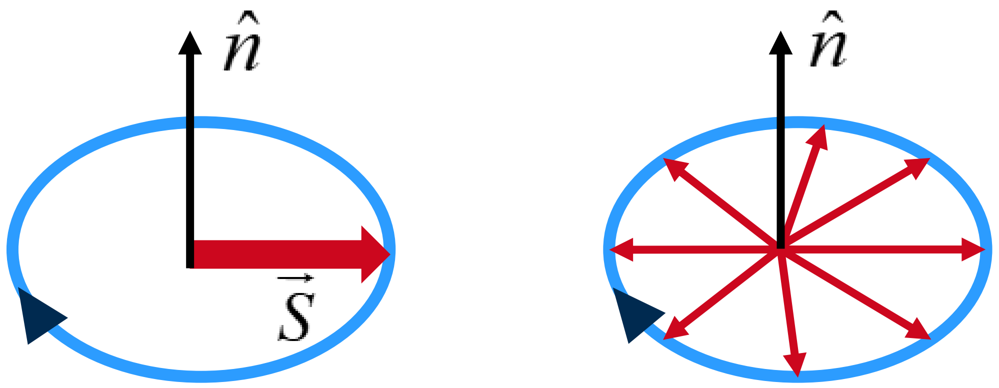
- Beam emittance
- Momentum spread
- 1st & 2nd order effects
- Orbit deviations

Optimization:

- Electron Cooling
- Beam bunching
- Sextupole corrections

- Spin tune: $\nu_s = \gamma G$

  number of spin precessions per turn.



At beginning

After some time

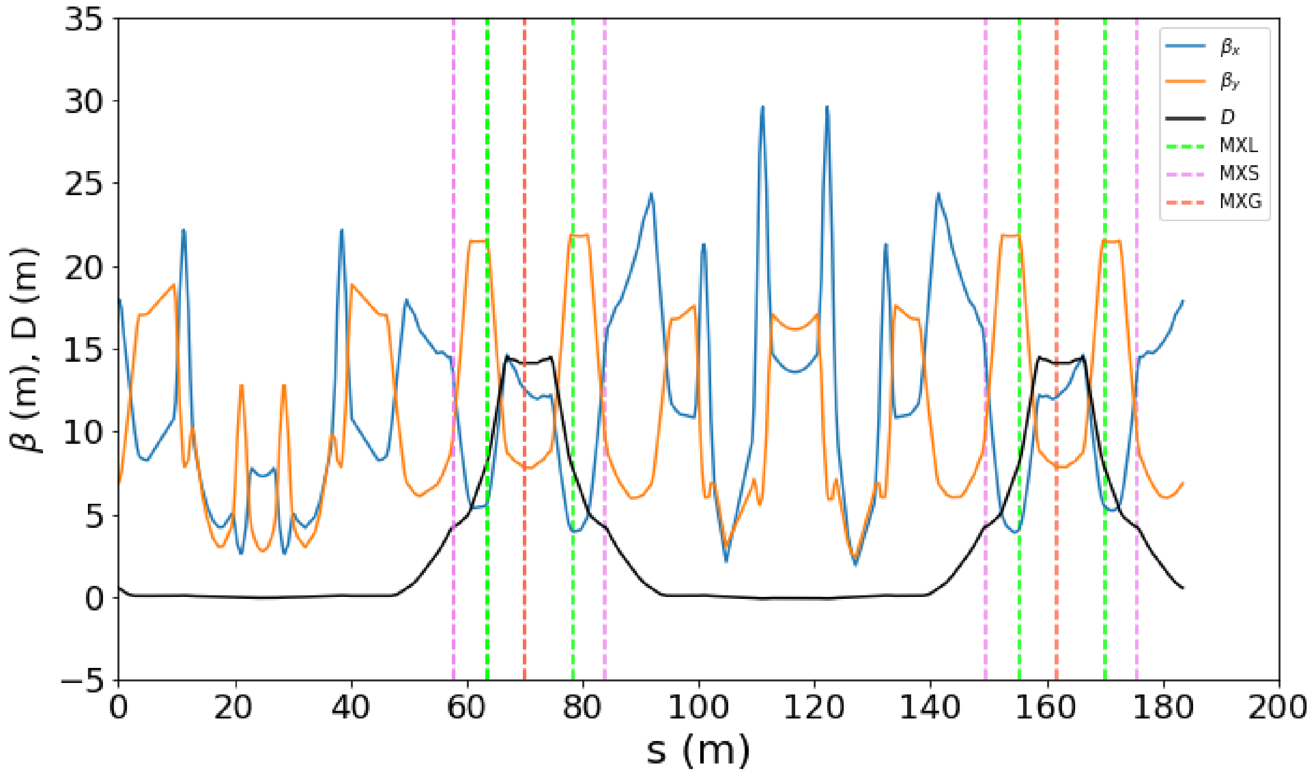
SEXTUPOLE CORRECTIONS

- Correction effects of sextupole: [1]
  - orbit lengthening

$$\left(\frac{\Delta L}{L}\right)_\beta = \mp\frac{k_2 D_0 \beta_{x,y}\varepsilon_{x,y}}{L}$$

  - 2nd-order momentum compaction factor

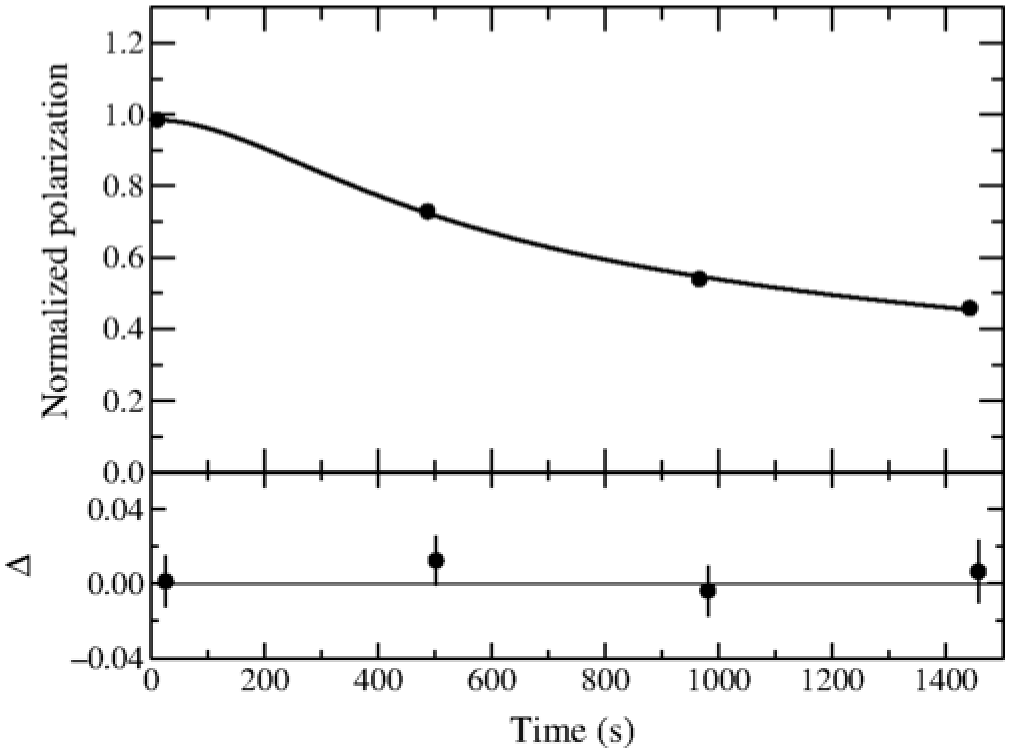
$$\Delta\alpha_1 = -\frac{k_2 {D_0}^3}{L}$$



Three or more families of sextupole are needed.

SPIN COHERENCE TIME RECORD

- SCT > 1000 *s* achieved at COSY [2]
- With about 10^9 stored deuterons.
- Long SCT was one of main obstacles of storage ring EDM experiments.
- SCT of crucial importance, since $\sigma_{stat} \propto \frac{1}{\tau_{SCT}}$



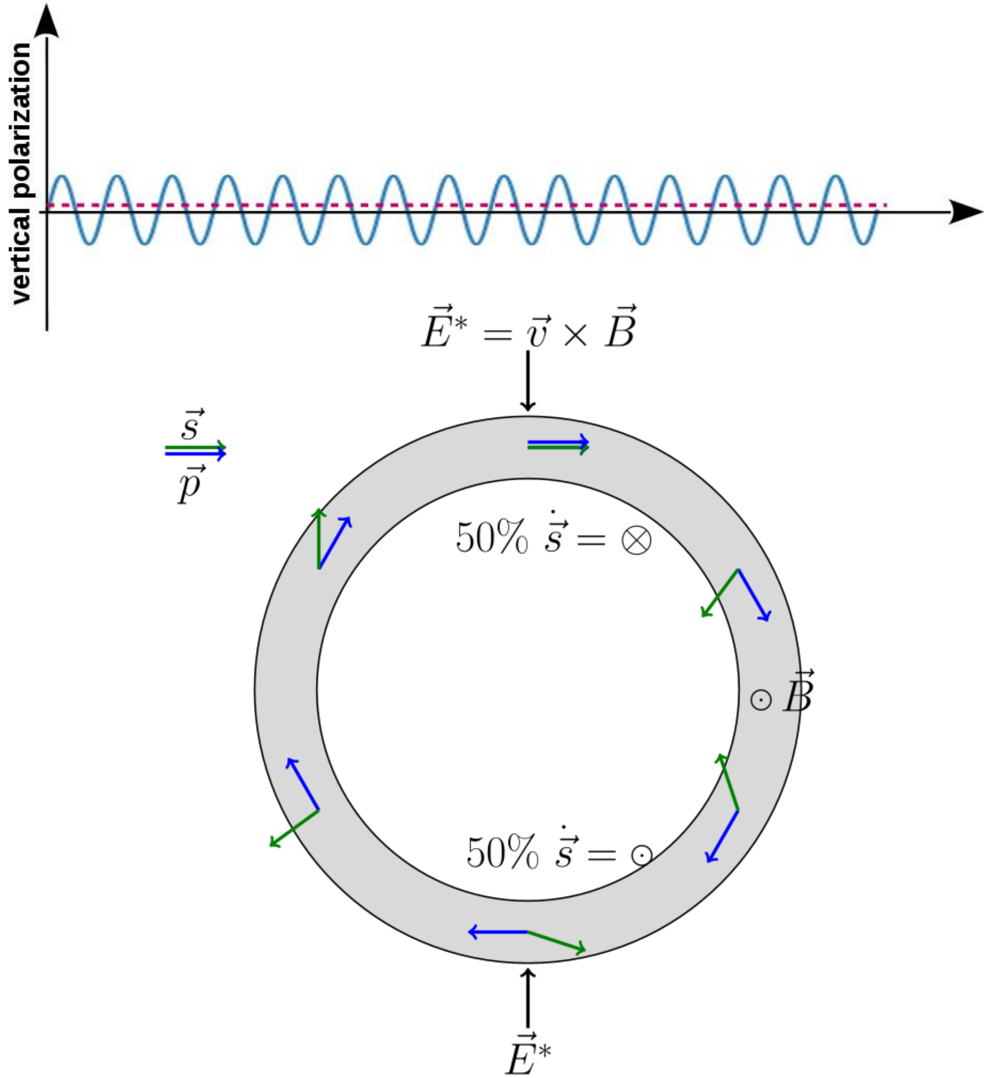
WIEN FILTER

- Frozen spin: $\vec{\Omega}_{MDM} = 0 \rightarrow$ vertical build up.

- Problem: in a pure magnet ring, $\vec{\Omega}_{MDM} \neq 0$,

  $\rightarrow$ no accumulation of vertical asymmetry.

- Solution: RF-Wien Filter



WIEN FILTER

Solution: RF-Wien Filter

- Lorentz force: $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0$

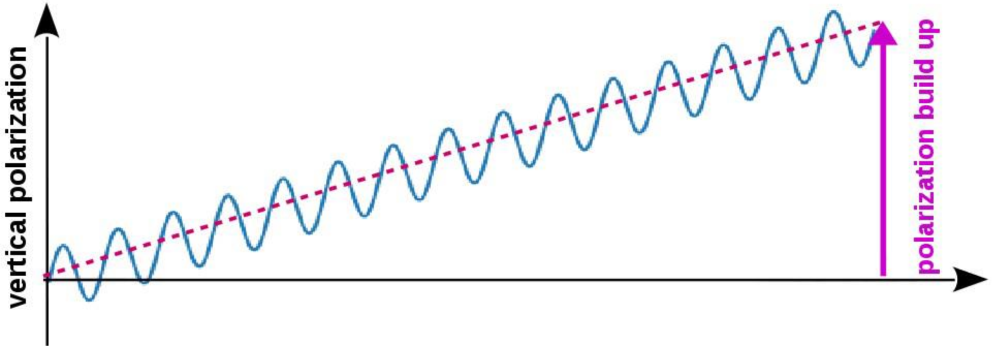
→ particle trajectory is not affected

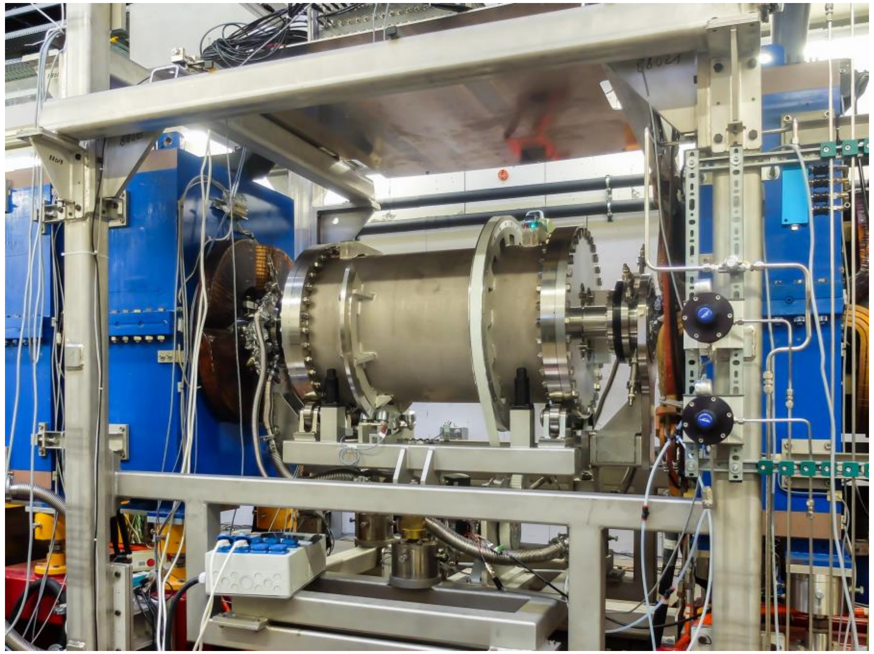
- $\vec{B} = (0,\ B_y,\ 0)$ and $\vec{E} = (E_x,\ 0,\ 0)$

→ spin motion is influenced

- RF-Wien Filter fields

→ oscillate at a harmonic of the spin precession freq.

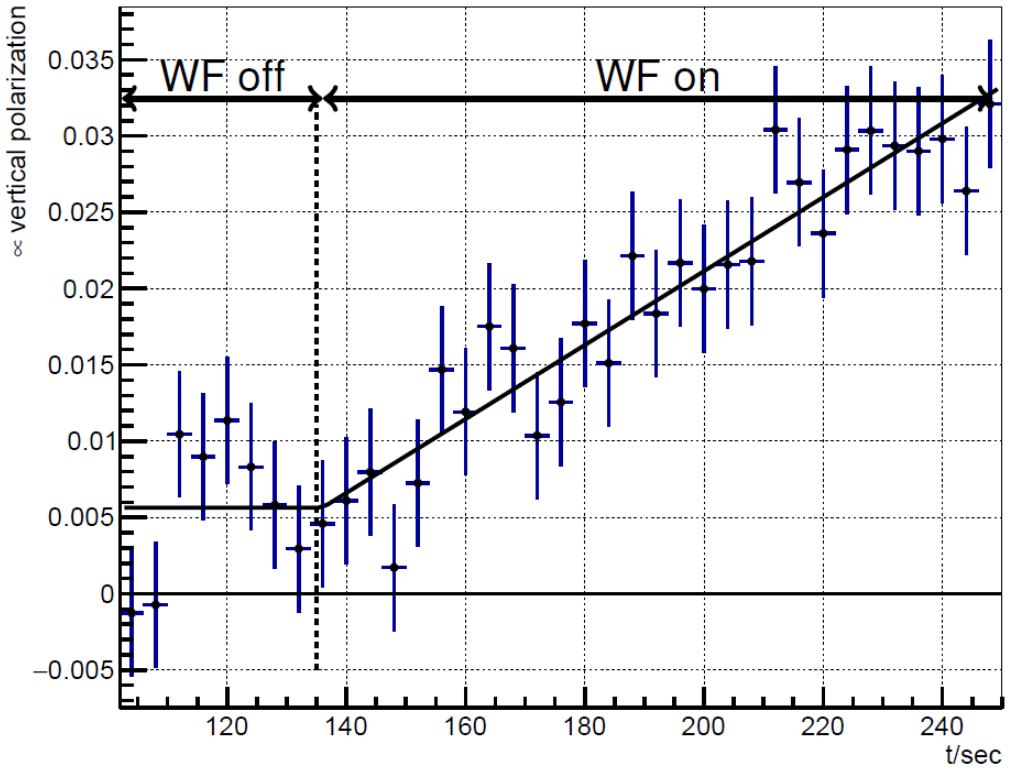




WF induced spin resonance → vertical build up.

OBSERVATION OF POLARIZATION BUILD-UP

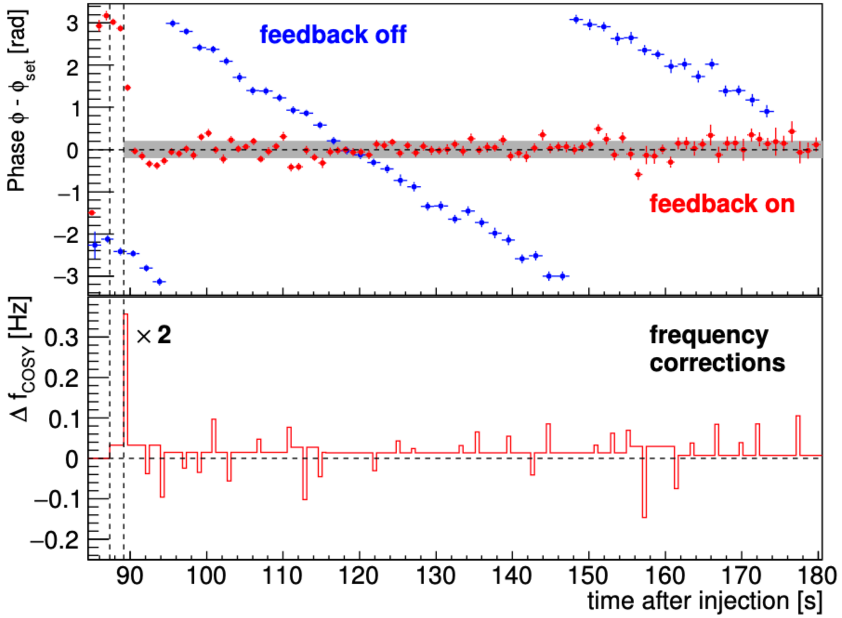
- RF-Wien Filter ON: vertical polarization build-up proportional to EDM .
- Problem: ring imperfections (magnet misalignments,..) lead to perturbations.
- Perturbations are under investigation

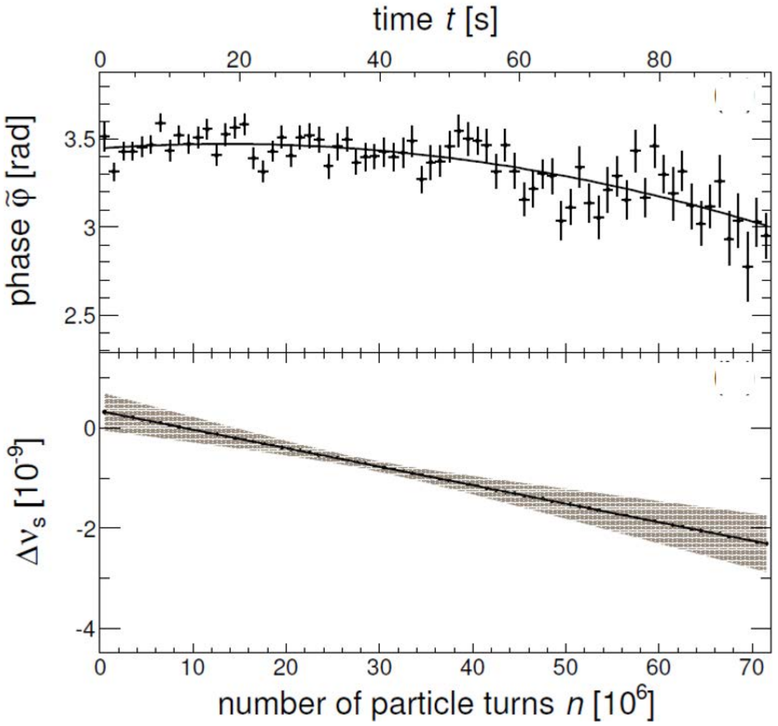


RESULTS FROM PRECURSOR EXPERIMENT

Tools developed to manipulate and measure beam polarization

- reaching > 1000 s spin coherence time
- measure 120 kHz spin tune precession in horizontal plane to 10^{-10} in 100 s
- development of polarization feed back system
- single bunch spin manipulation
- RF Wien filter, BPMs, deflector, polarimeter, . . .



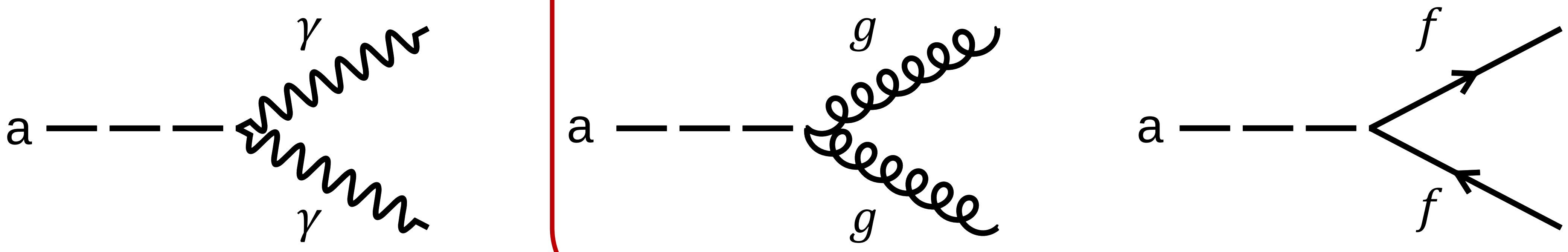


AXION SEARCHES

AXIONS/AXION LIKE PARTICLES (ALPS)

- Axions are leading particle candidates for dark matter.
- Possible couplings to standard model particles:

$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$



storage ring experiments

- For low mass ($< 10^{-7}\,\mathrm{eV}/c^2$), ALPs dark matter can be expressed as a classical field:

$$a(\mathrm{t}) = a_o \cos(\omega_a t + \varphi_o).$$

SPIN MOTION

- Spin motion in a purely magnetic ring:

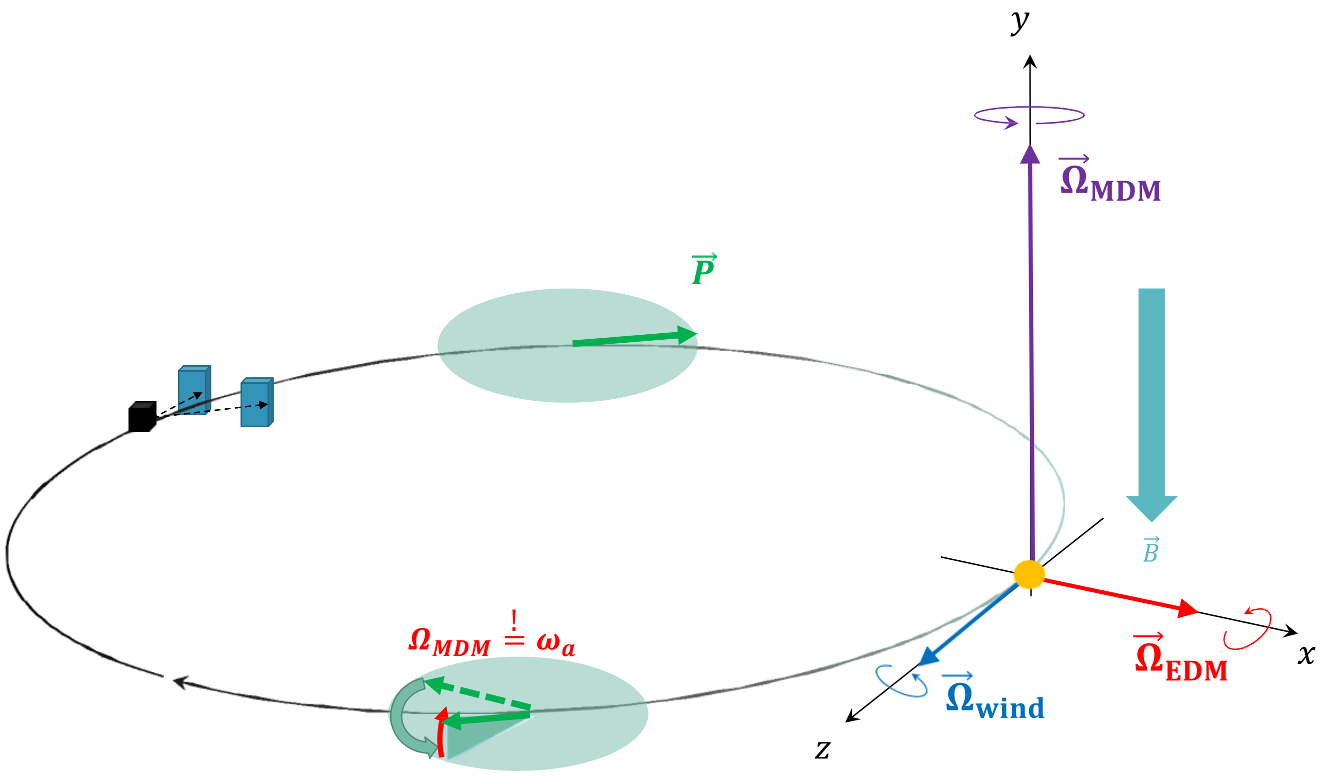
$$\frac{d\vec{S}}{dt} = (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM} + \vec{\Omega}_{wind}) \times \vec{S}$$

$$\vec{\Omega}_{MDM} = -\frac{q}{m} G\vec{B}, \qquad \vec{\Omega}_{EDM} = -\frac{1}{S\hbar} dc\vec{\beta} \times \vec{B},$$

$$\vec{\Omega}_{wind} = -\frac{1}{S\hbar}\frac{C_N}{2f_a}(\hbar\partial_0 a(t))\vec{\beta},$$

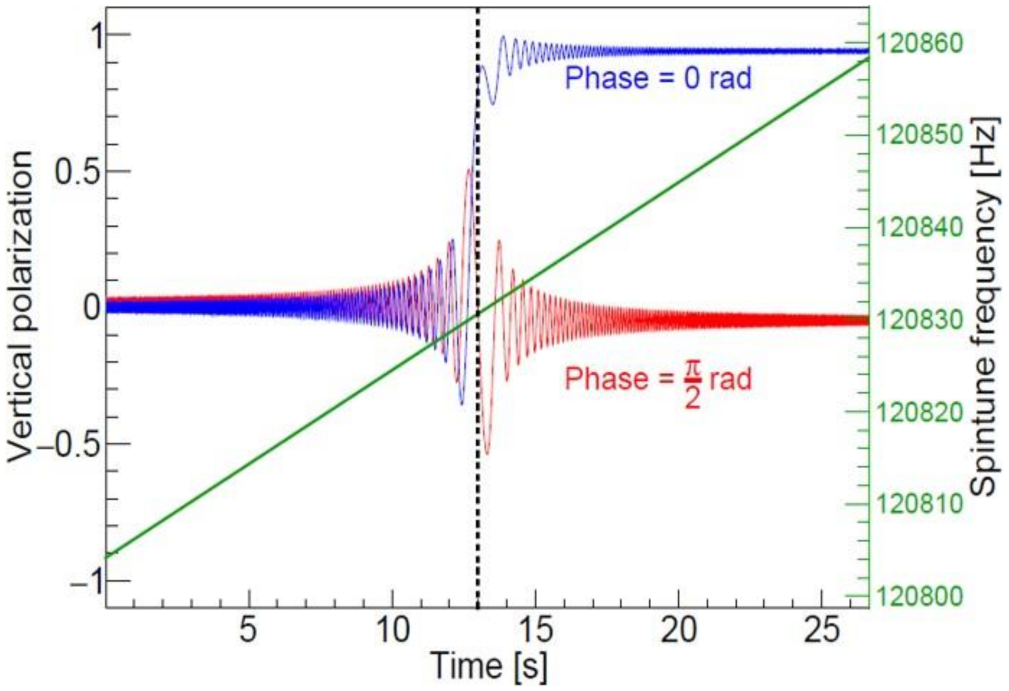
- Axion/ALPs – gluon coupling induces an oscillating electric dipole moment (oEDM):

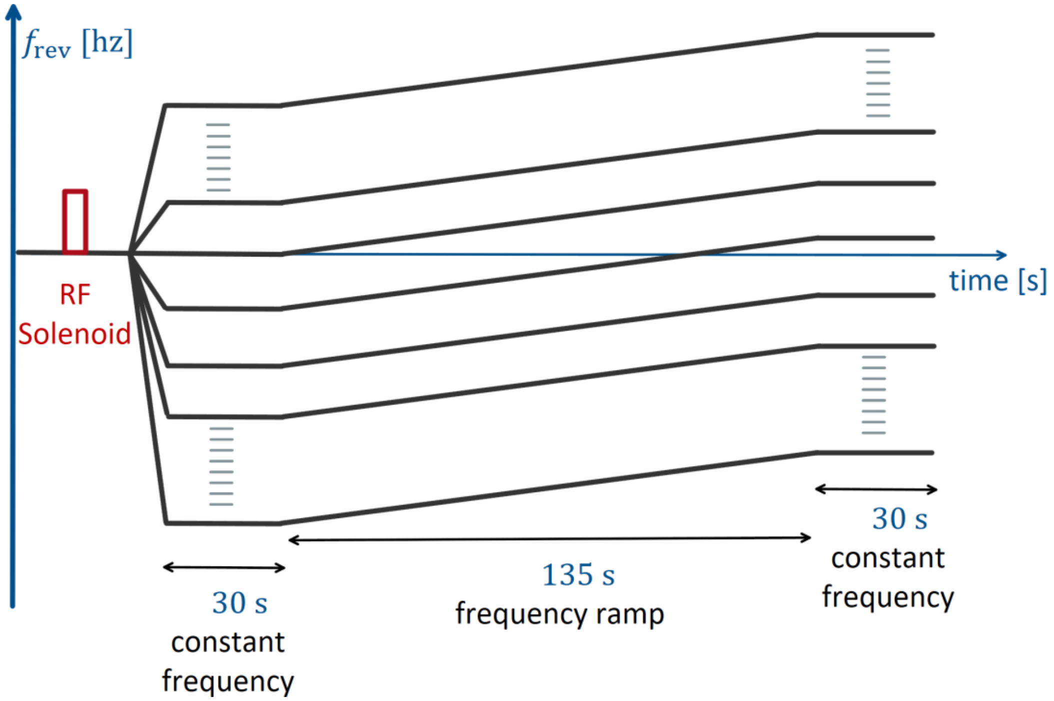
$$d = d_{DC} + d_{AC}\cos(\omega_a t + \varphi_o).$$



Resonant build-up of vertical polarization, when $m_a c^2 \equiv \hbar\omega_a = \hbar\Omega_{MDM}$

SCAN THE FREQUENCY FOR RESONANCE





Unknown frequency ω_a

- Scan the frequency for resonance
- Signal: Jump in vertical polarization, when $\omega_a = \Omega_{MDM}$

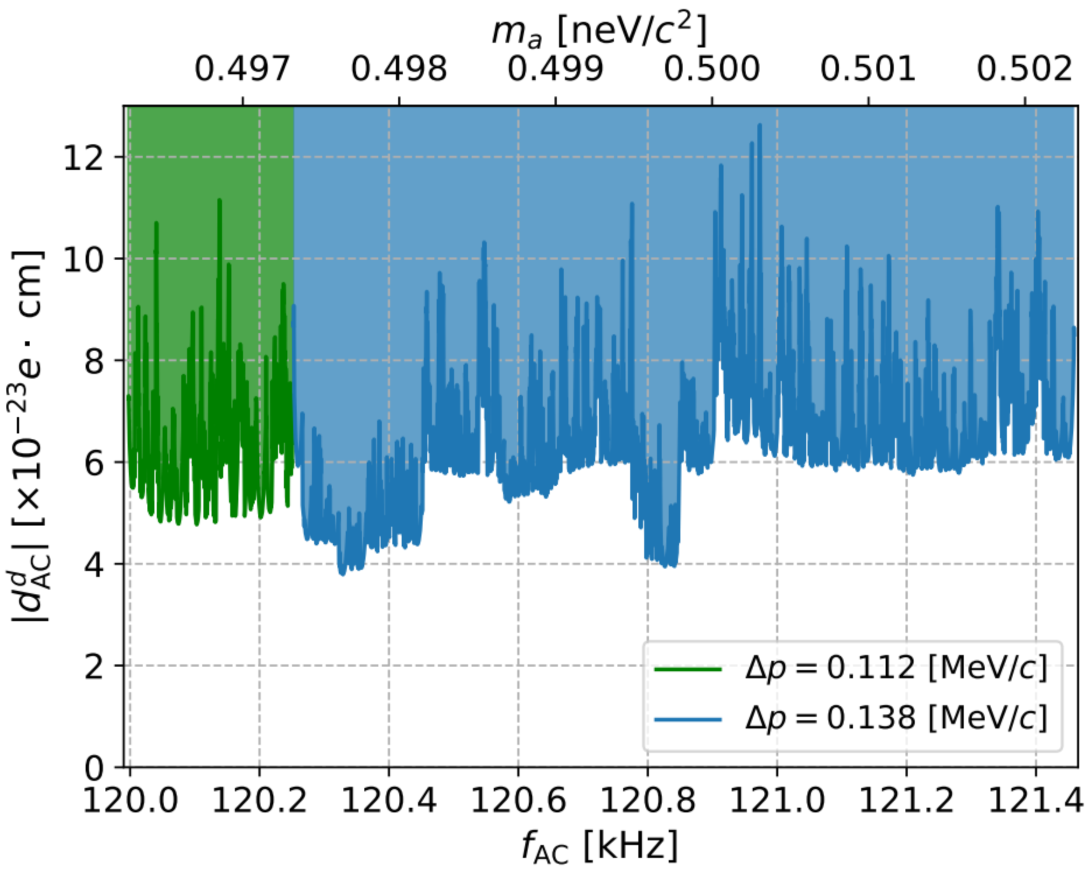
Unknown phase ϕ_a

- Use beams with perpendicular polarization: 4 bunches
- You cannot miss the signal.

RESULTS ON OSCILLATING EDM

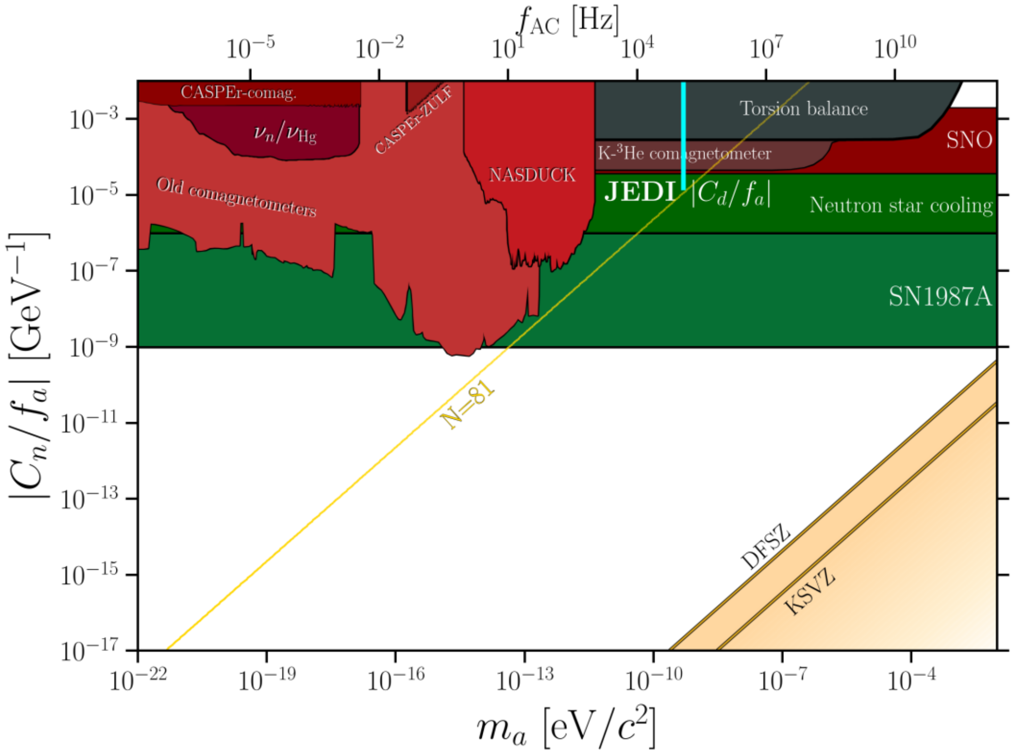
- First proof-of-principle experiment was performed at COSY, FZ Jülich. [3]
- Polarized deuteron beam: 970 MeV/c
- Only a few days of data taking.

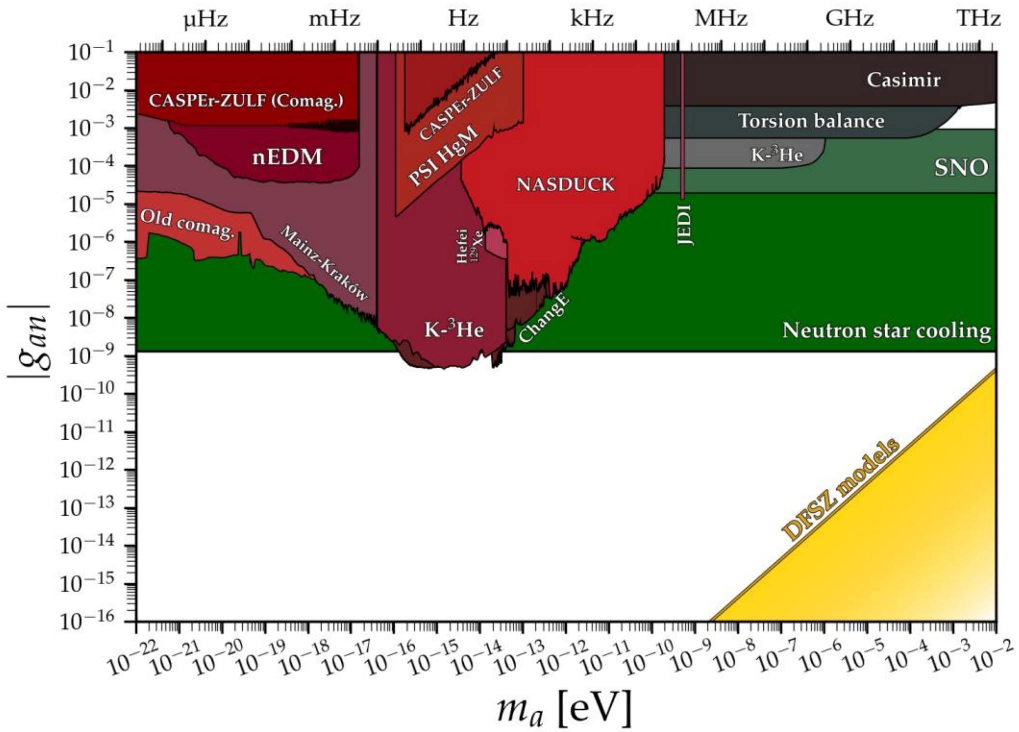
- 90% CL upper limit on the ALPs induced oscillating EDM.



BOUND ON AXION-NUCLEON COUPLING

- Limits on axion/ALP neutron coupling from the Particle Data Group 2023
- It includes the result from the JEDI collaboration





NEXT STEPS

STAGED APPROACH

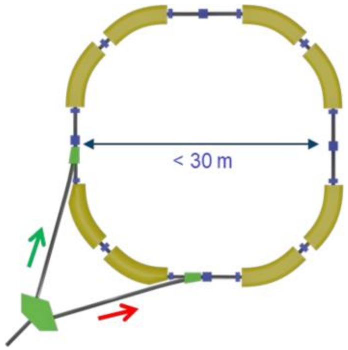
Stage 1

- Precursor experiment

- magnetic ring
- proof-of-capability
- 1^{st} dEDM & axion measurements

Stage 2

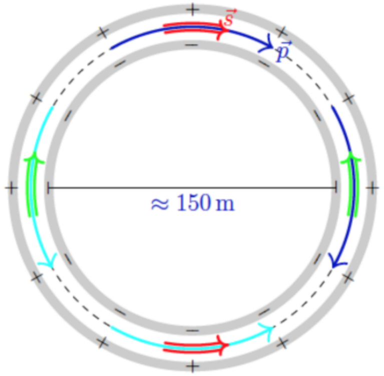
- Prototype ring



- electric/magnetic bends
- simultaneous clockwise (CW) and CCW beams
- develop key technologies
- 1^{st} proton EDM measurement

Stage 3

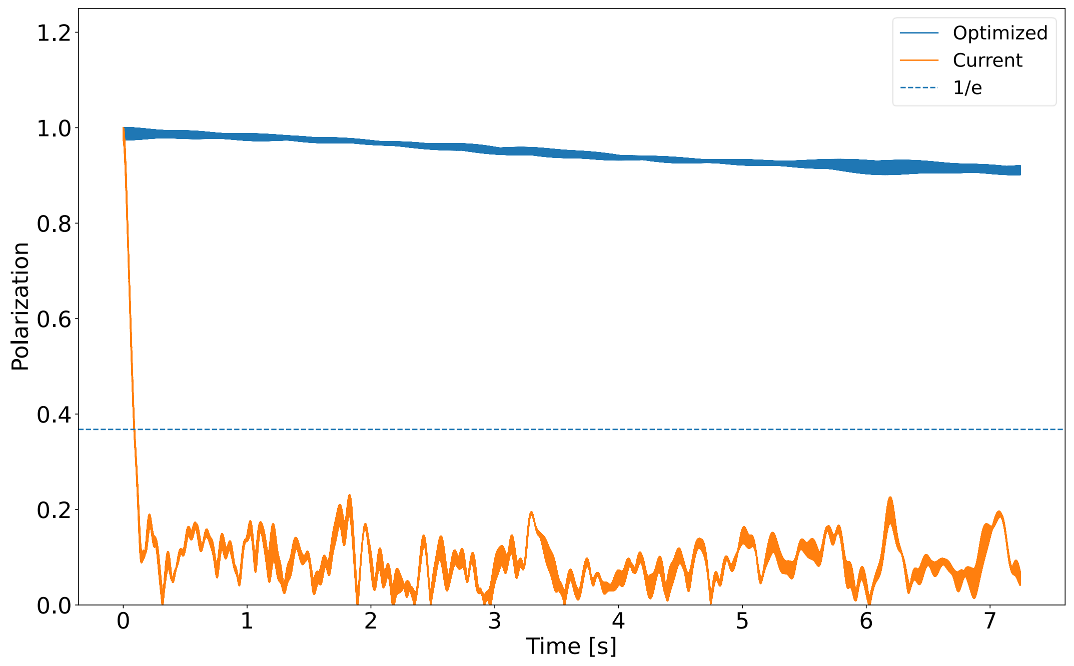
- Dedicated storage ring



- pure electrostatic ring
- proton magic momentum ($p = 701$ MeV/c)

POSSIBLE FUTURE EXPERIMENTS AT GSI/FAIR

- existing accelerators at GSI/FAIR with polarized hadron beams
- letter of intend (LOI) has been submitted to G-PAC
- preliminary simulations suggest that 3 groups of sextupoles are required (**see my poster**)



SUMMARY

- Storage ring experiments offer new possibilities for searching EDM and Axions / ALPs.
- First measurements of static and oscillating deuteron EDM at COSY, FZ Jülich.
- Next step: Prototype EDM ring development.
- Experiments can be performed at GSI/FAIR or other storage rings, wherever polarized hadron beams available.

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- Karanth, S, et al. "First Search for Axion-Like Particles in a Storage Ring Using a Polarized Deuteron Beam." Physical Review X 13 (2023): 031004.
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Thank you for your attention!

HOW TO EXPLORE A WIDER MASS RANGE

- $\Omega_{MDM} = \gamma G \Omega_{rev}$, a wide mass range can be covered by:

1) vary the beam energy (γ and Ω_{rev})
2) use different nuclei (G - factor)
3) with additional electric field (frozen spin method)

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

PRECISION DETERMINATION OF SPIN TUNE

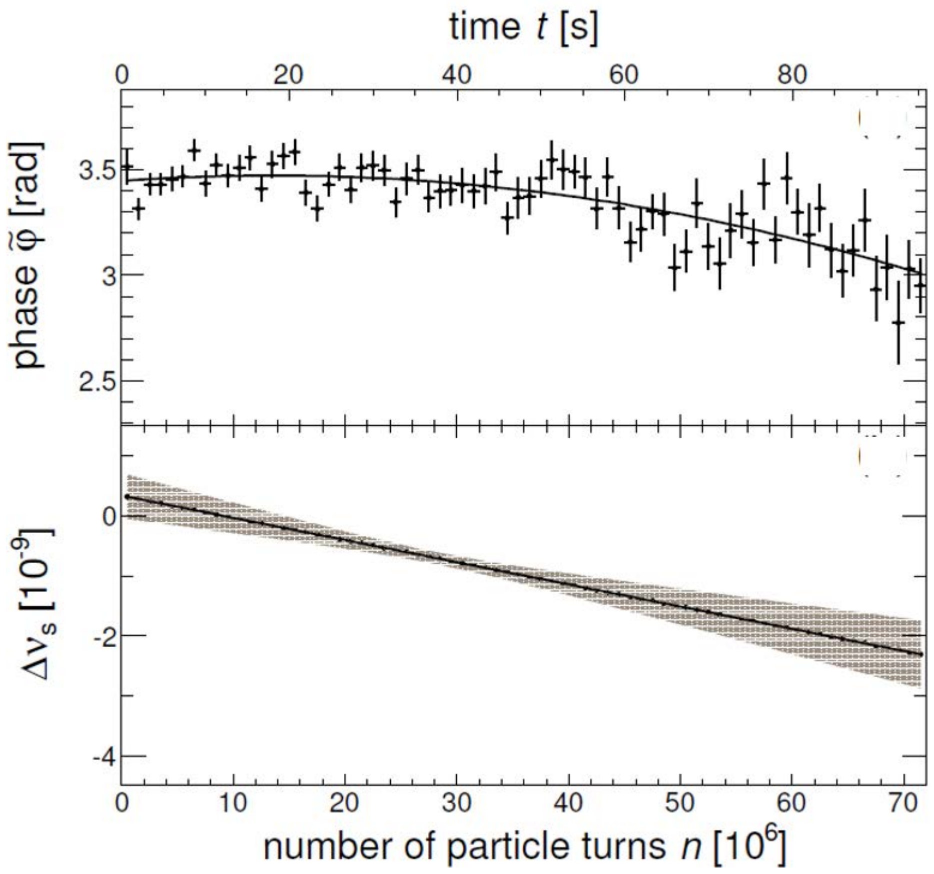
- Spin tune = number of spin precessions per turn.

$$\nu_s = \gamma G$$

- Spin tune:

  $\sigma(\nu_s) \approx 10^{-10}$ in 100 s time interval.

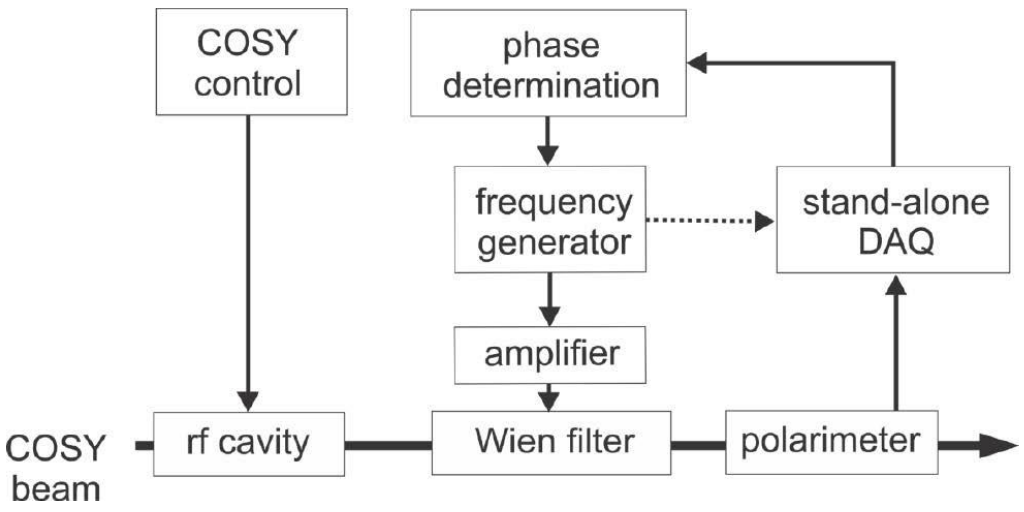
  $\sigma(\nu_s) \approx 10^{-8}$ in 2 s time interval.

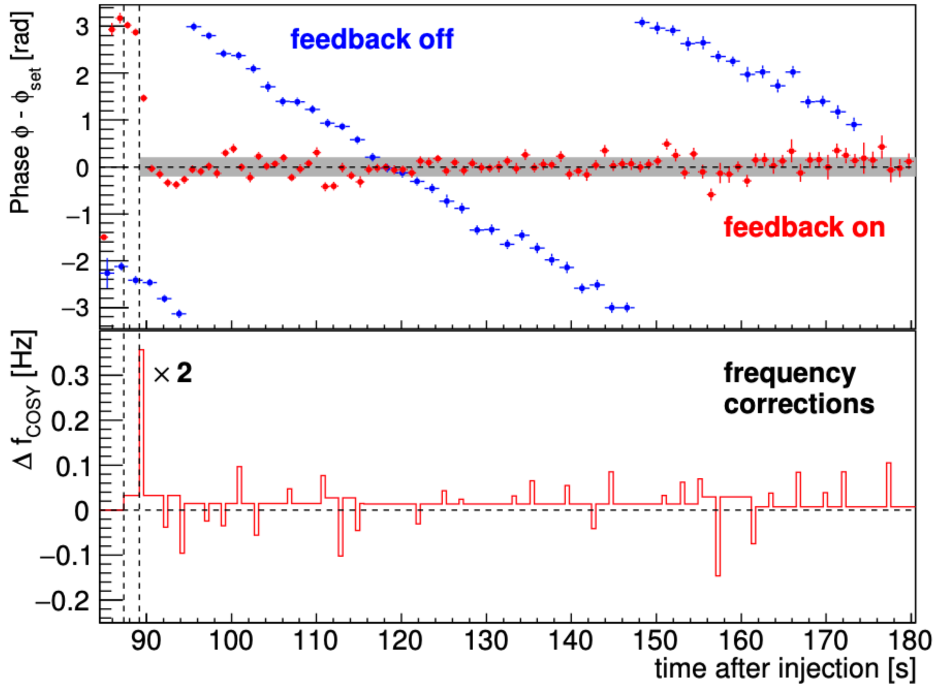


The preservation of the polarization is of crucial importance.

POLARIZATION FEEDBACK

- No frozen spin at COSY
  → phase-lock between spin-precession and RF device.





Achievement : error of phase-lock $\sigma_\varphi = 0.21\,\mathrm{rad}$

POSSIBLE FUTURE EXPERIMENTS AT GSI/FAIR