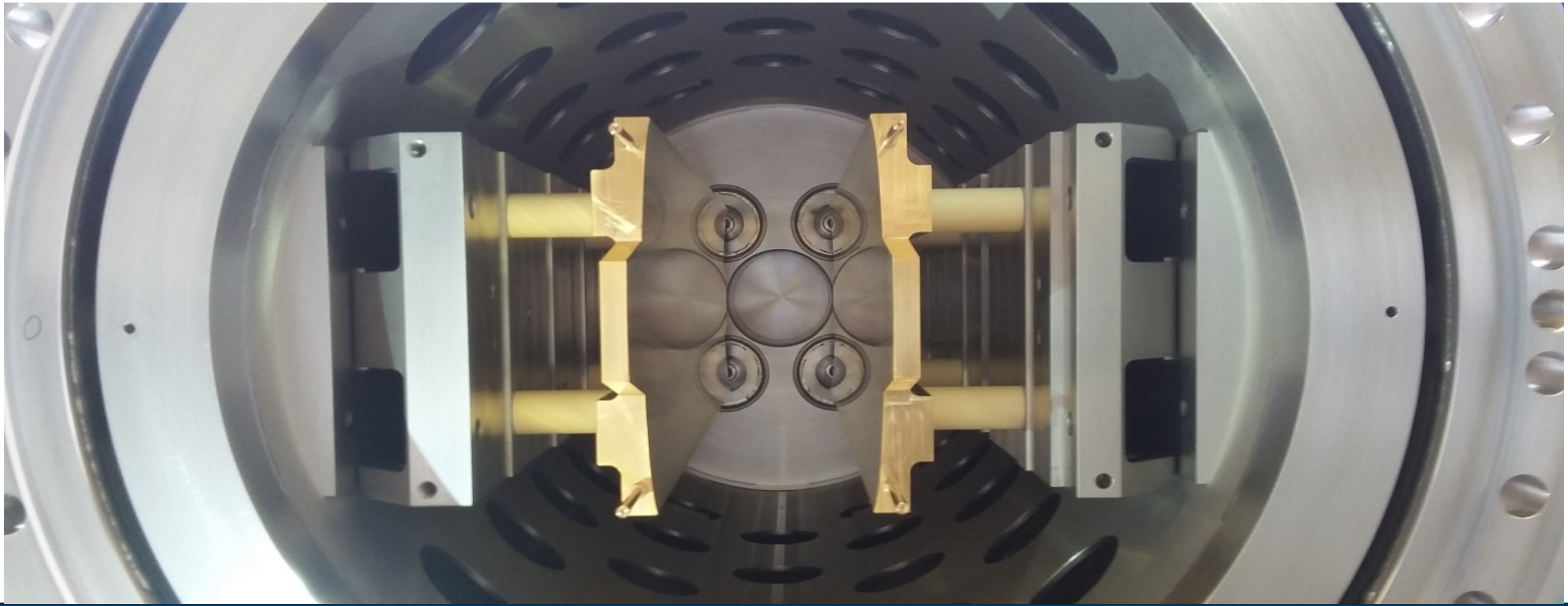


MEASUREMENT OF THE DEUTERON ELECTRIC DIPOLE MOMENT USING A STORAGE RING

SPIN'23, DURHAM CONVENTION CENTER 09/25/2023 VERA SHMAKOVA

JEDI

MATTER-ANTIMATTER ASYMMETRY

- Why Universe Matter dominated?

• Experiment: *V. Barger, et al, Phys.Lett.B566, 8 (2003)*	$\frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$
• Expectation from SCM: *W. Bernreuther, Lect. Notes Phys.591, 237 (2002)*	$\frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-18}$

- Preference of matter (A. Sakharov criteria, 1967)

$\boxed{\textbf{\textit{CP} violation}}$

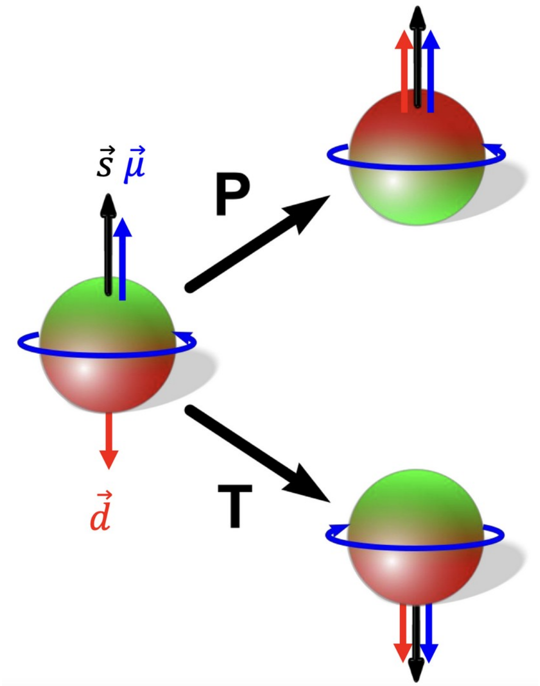
- *CP* violation in SM is not sufficient

ELECTRIC DIPOLE MOMENT

- EDM violates both T, P symmetries

- EDM violates CP symmetry (if CPT conserved)

- EDM may possibly contain the missing cornerstone to explain the matter-antimatter asymmetry



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

$$\mathcal{P}:\quad H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$

$$\mathcal{T}:\quad H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$

EDM AT STORAGE RINGS

THOMAS - BMT EQUATION:

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

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

$$\vec{\Omega}_{EDM} = -\frac{\eta q}{2mc}\{\vec{E} + c\vec{\beta}\times\vec{B}\}$$

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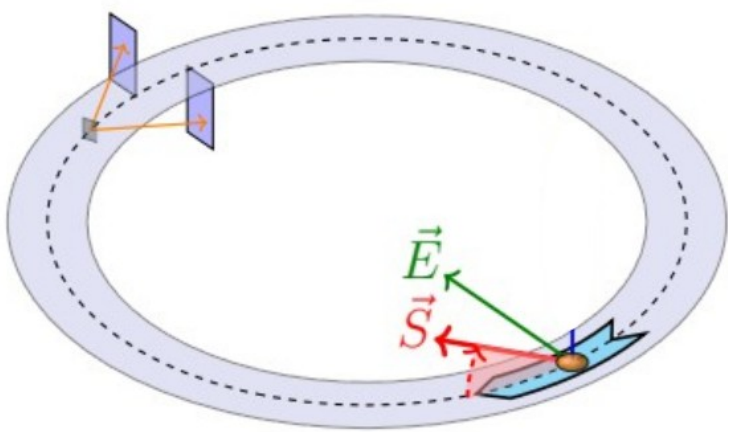
$$\vec{\Omega}_{EDM} = -\frac{\eta q}{2mc}\{\vec{E} + c\,\cancel{\vec{\beta}\times\vec{B}}\}$$

"Frozen spin": in the absence of EDM spin stay aligned to momentum

In case of purely electric ring:

- magnetic field is absent
- momentum is chosen that term $(G - \frac{1}{\gamma^2 - 1}) = 0$

⇨ radial electric field causes the spin to precess out of the plane linearly



EDM FOR CHARGED PARTICLE IN 3 STAGES

***see talk of Frank Rathmann, Thursday 18:00**

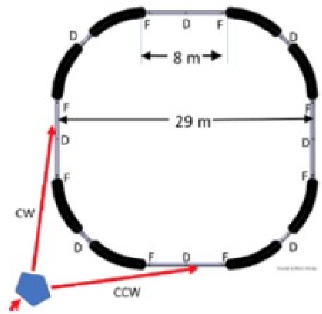
Stage 1

- precursor experiment

pure magnetic ring

Stage 2

- prototype ring



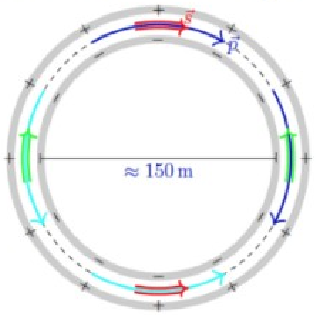
combined E/B ring

simultaneous CW-CCW beams

frozen spin

Stage 3

- dedicated storage ring



all electric proton ring

simultaneous CW-CCW beams

frozen spin

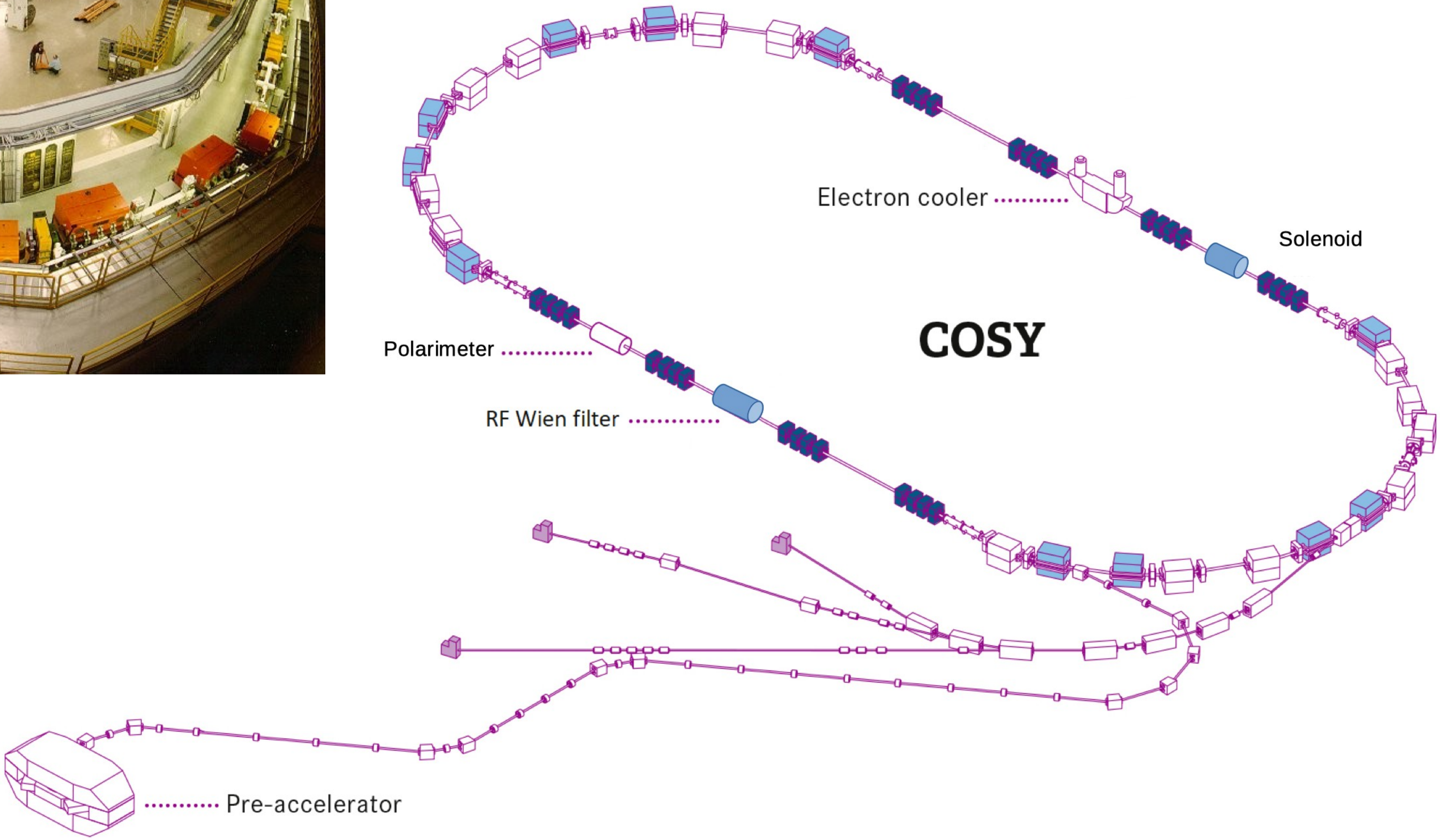
$\sigma_{EDM}/(e \cdot \mathrm{cm})$

10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21} 10^{-22} 10^{-23} 10^{-24} 10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29}

* F. Abusaif et al., "Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study," 2019.https://arxiv.org/abs/1912.07881

PRECURSOR EXPERIMENT AT COSY

COoler SYnchrotron COSY:
- magnetic storage ring
- polarized protons and deuterons
- momenta p = 0.3 – 3.7 GeV/c
- starting point for EDM measurement



EDM AT MAGNETIC RING

THOMAS - BMT EQUATION:

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

$$\vec{\Omega}_{EDM}=-\frac{\eta q}{2mc}\{\cancel{\vec{E}}+c\,\vec{\beta}\times\vec{B}\}$$

MDM causes fast spin precession in horizontal plane

In **pure magnetic ring** motional electric field term $(c\,\vec{\beta}\times\vec{B})$

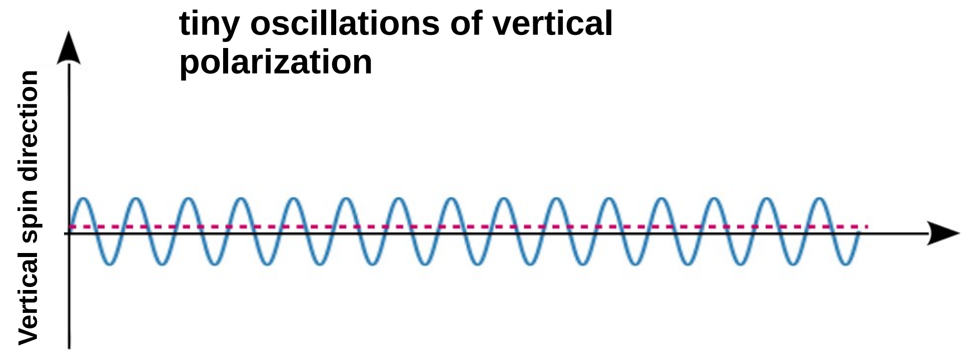
⇩

access to EDM

RF WIEN FILTER

In the magnetic ring
momentum ↑↑ spin ⇨ spin kicked up
momentum ↑↓ spin ⇨ spin kicked down

no accumulation of vertical asymmetry



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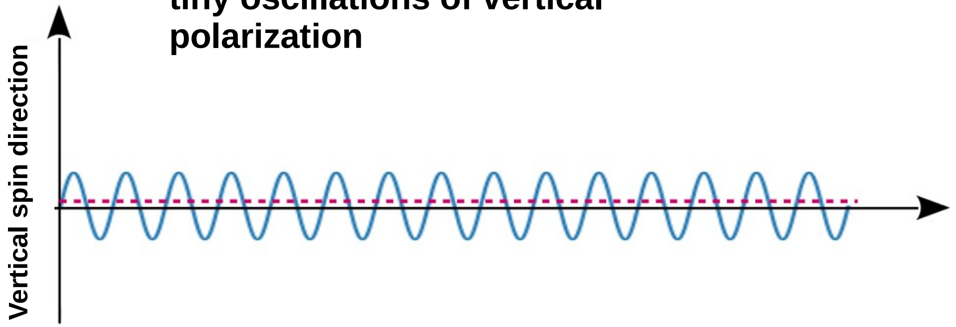
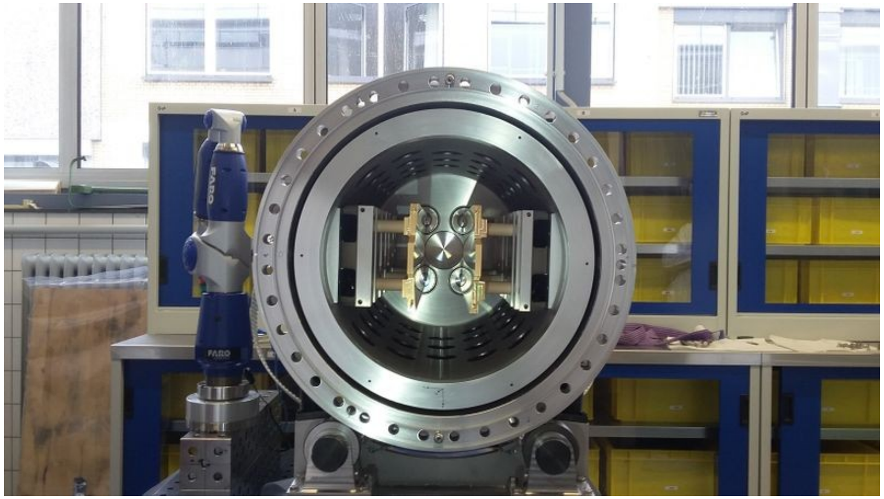


RF Wien filter

Heberling, Hölscher and ***J. Slim***

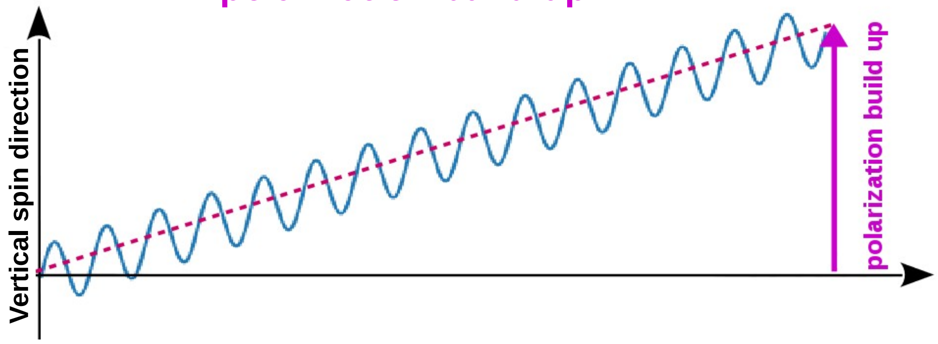
J. Slim et al. Nucl. Instrum. Methods Phys. Res. A 828, 116 (2016)

- Lorentz force $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0$
- $\vec{B} = (0, B_y, 0)$ And $\vec{E} = (E_x, 0, 0)$
- provides $\vec{E} \, x \, \vec{B}$ by design



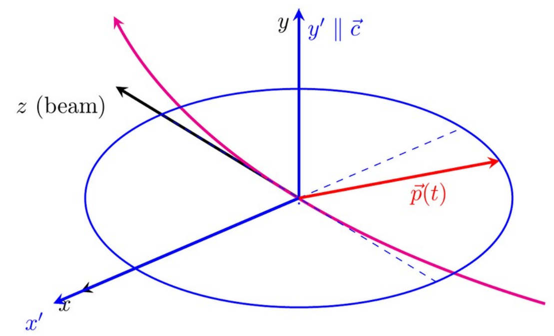
phase lock between spin precession and RF Wien filter

polarization build-up

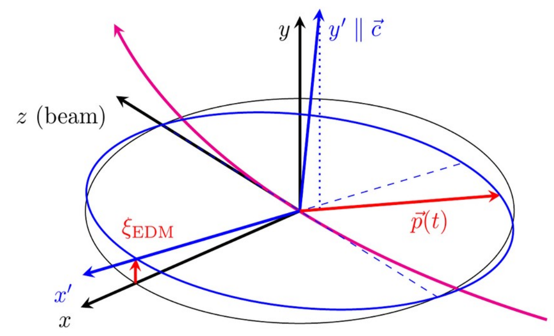


EFFECT ON INVARIANT SPIN AXIS

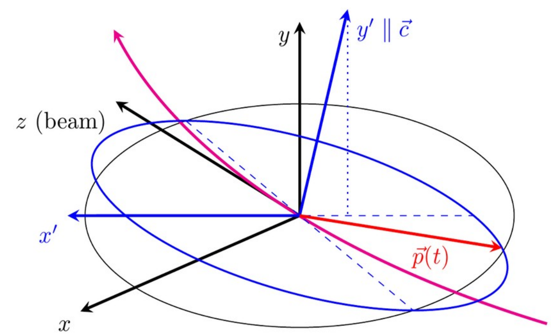
EDM absent



Pure EDM effect

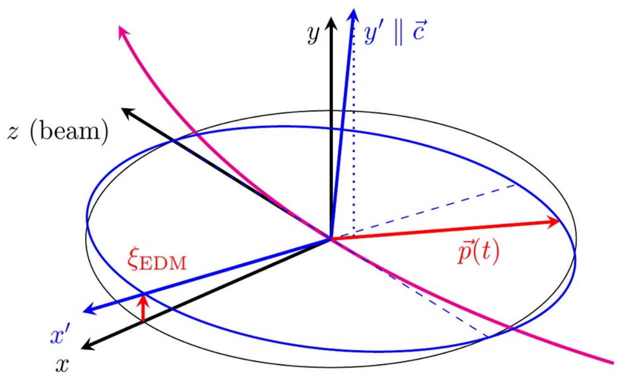


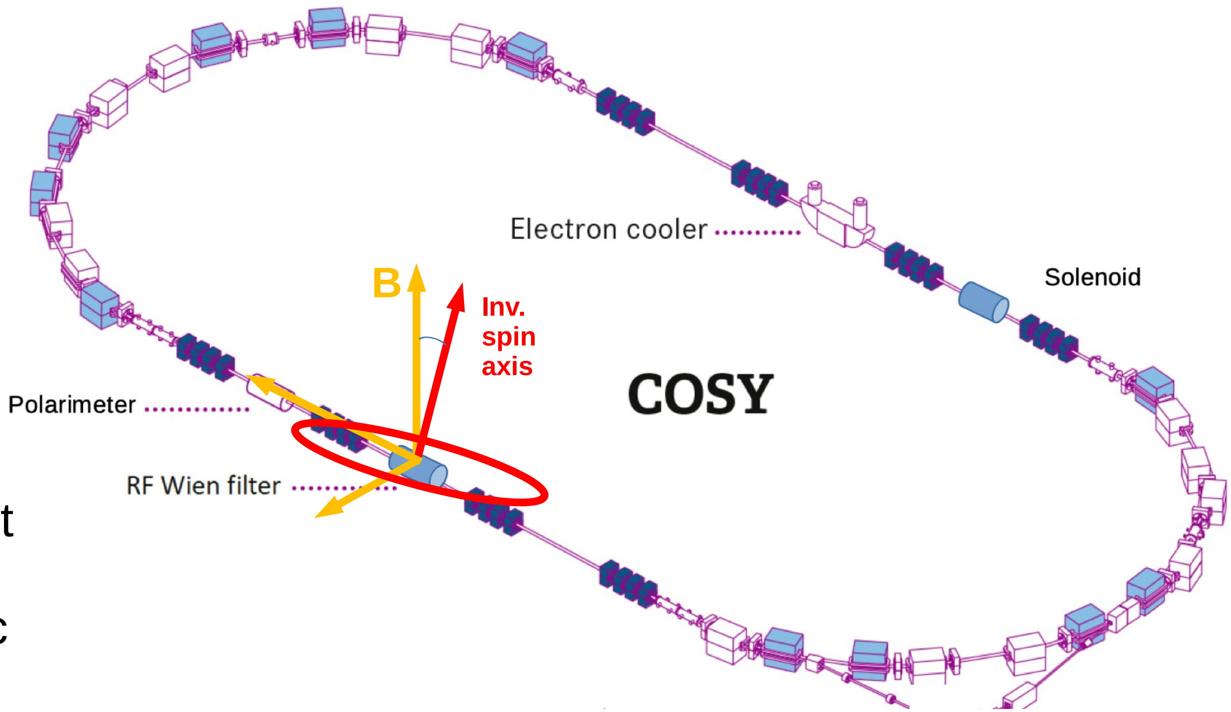
EDM + magnetic misalignments



MEASUREMENT OF THE EDM EFFECT

How the EDM effect actually measured:





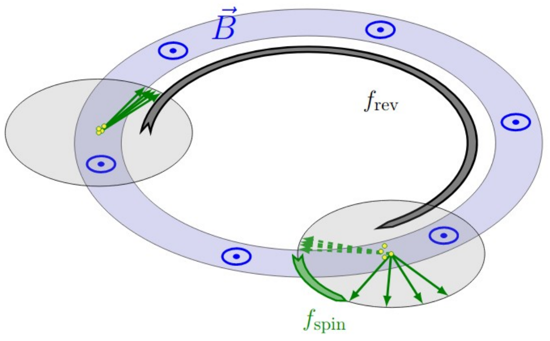
- The RF Wien filter is rotated about beam axis:
    - it generates radial magnetic field, which allows to compensate to radial tilt of invariant spin axis

- Solenoid introduces longitudinal magnetic field:
    - It change the invariant spin axis direction longitudinally

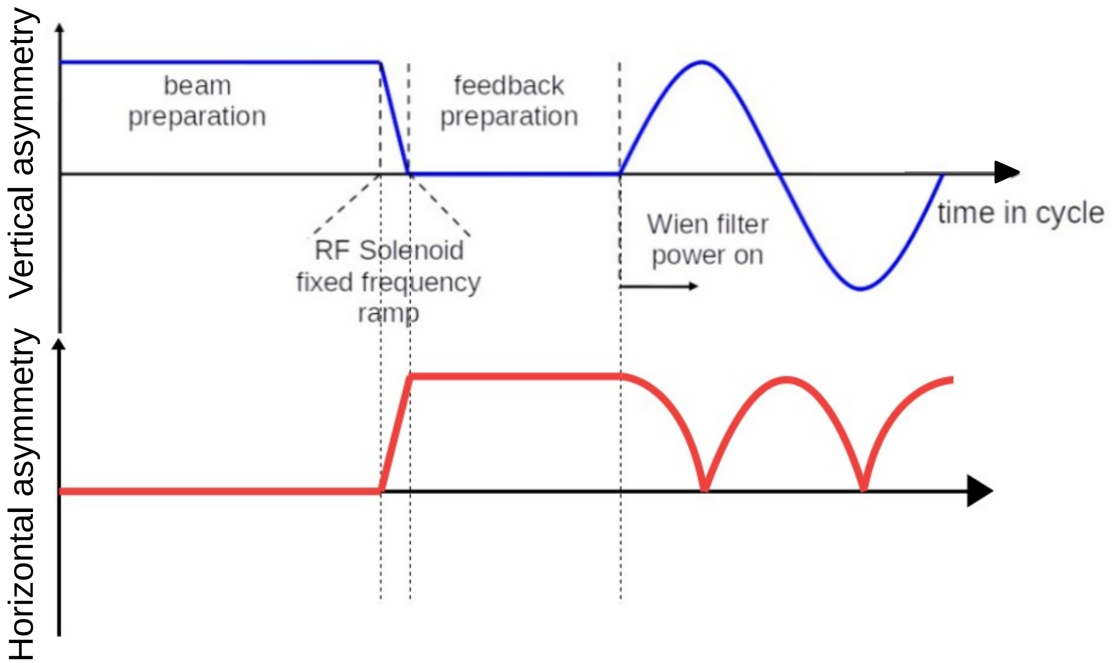
PRINCIPLE OF MEASUREMENTS

- Coherent ensembles in ring plane ➡ spin coherence time has to be longer then a measurement

- SCT > 1000 s.



Feedback: the basic workflow:

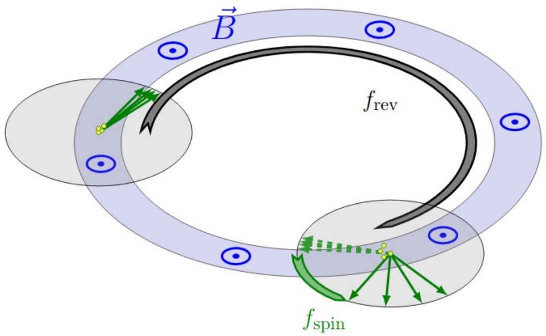


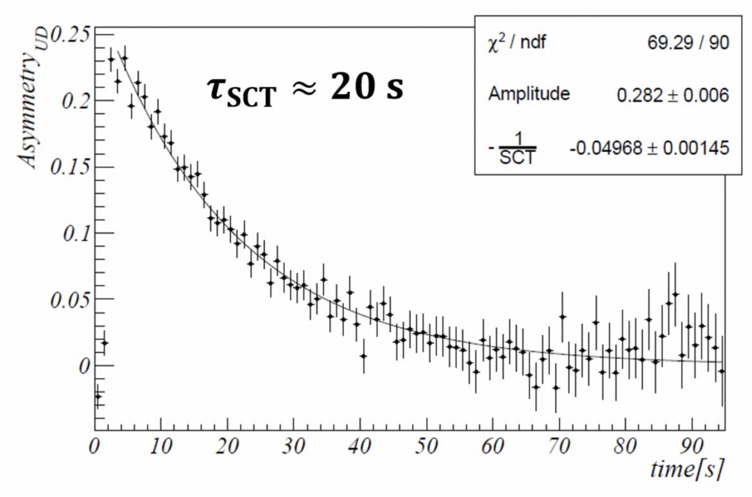
PRINCIPLE OF MEASUREMENTS

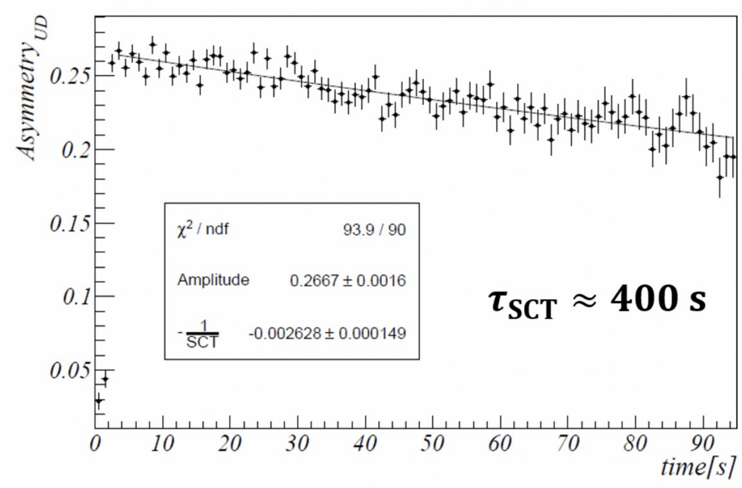
- Coherent ensembles in ring plane ➡ spin coherence time has to be longer then a measurement

- SCT > 1000 s.

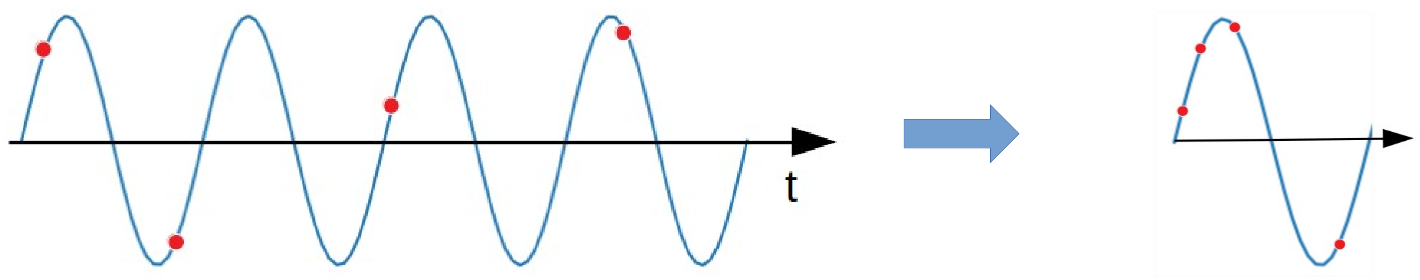
- Beam emittance and chromaticity was optimized to achieve long SCT





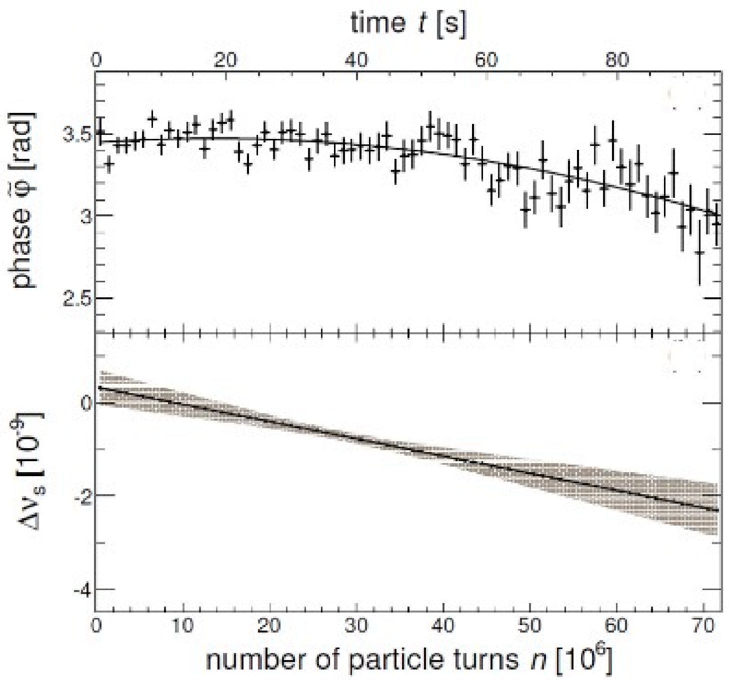


SPINTUNE MEASUREMENT



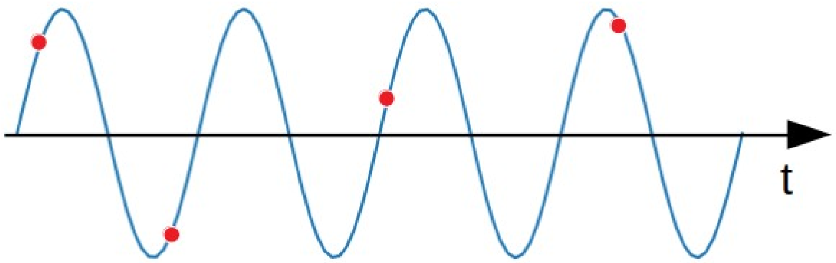
- Spin precesses with 120 kHz
- With event rates of ~ 15000 s^{-1}, there is 1 hit per 10 precessions.
- Not possible to resolve horizontal oscillation directly
- Spintune is determined in each time bin with monitoring phase of measured horizontal asymmetry with fixed spin tune:

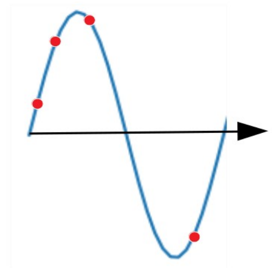
$$\nu_s(n) = \nu_s^{fix} + \frac{1}{2\pi}\frac{d\phi}{dn} = \nu_s^{fix} + \Delta\nu_s(n)$$

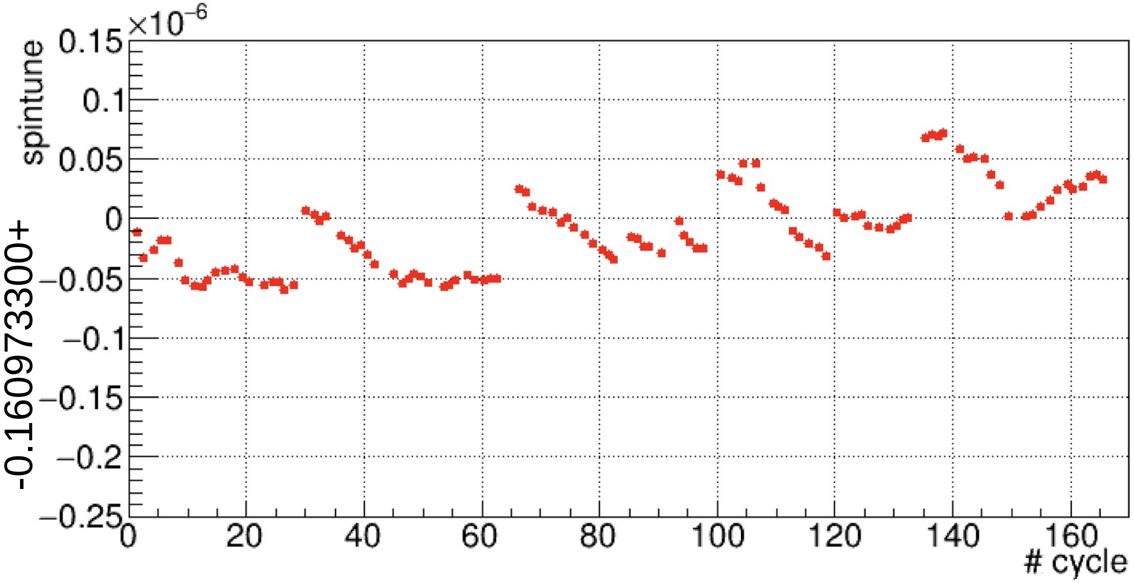


D. Eversmann et al. Phys. Rev. Lett. 115, 094801 (2015)

SPINTUNE MEASUREMENT







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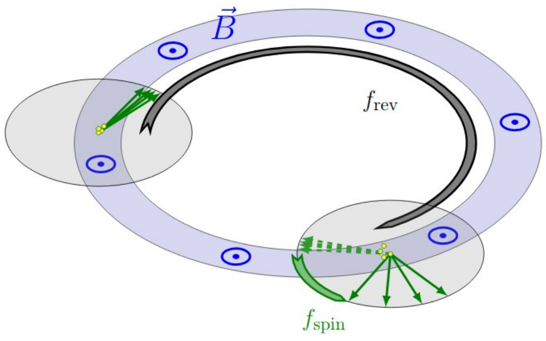
$$\nu_s(n)=\nu_s^{fix}+\frac{1}{2\pi}\frac{d\phi}{dn}=\nu_s^{fix}+\Delta\nu_s(n)$$

Spintune is a crucial precision tool used for
- horizontal polarization analysis and feedback system
- snake calibration
- study systematics effects in a ring

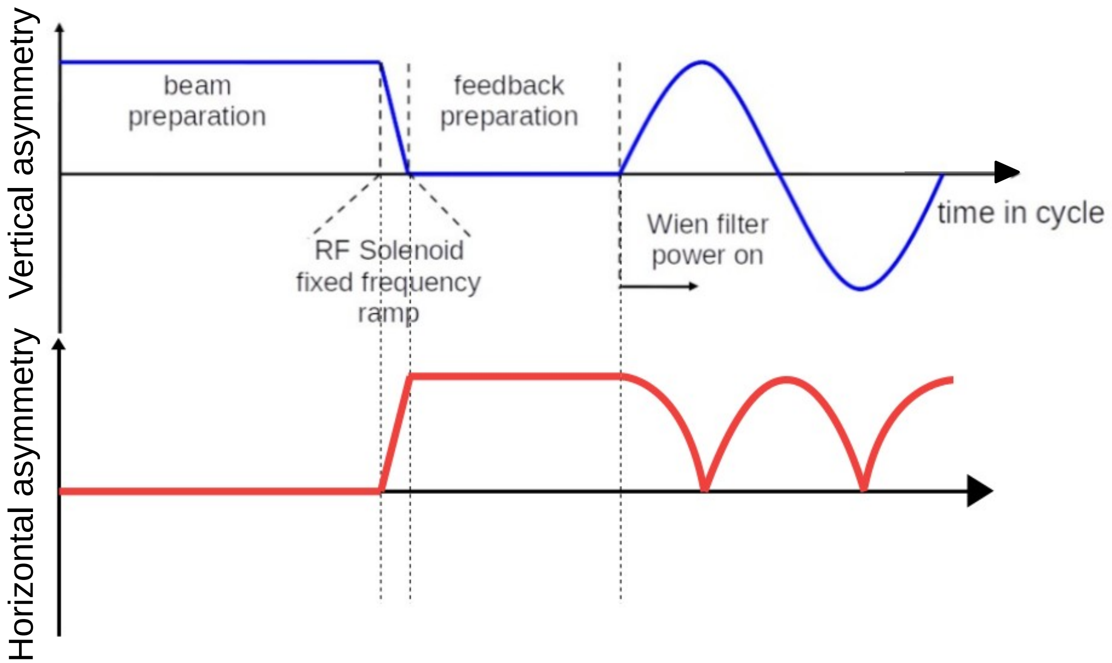
PRINCIPLE OF MEASUREMENTS

- Coherent ensembles in ring plane ➡ spin coherence time has to be longer then a measurement
- SCT > 1000 s.



- Spin precesses with 120 kHz.
- Wien filter operates on resonance: $f = f_{COSY} + f_{spin\ pres} = 871.430$ kHz
- Phase lock between spin precession and Wien filter RF

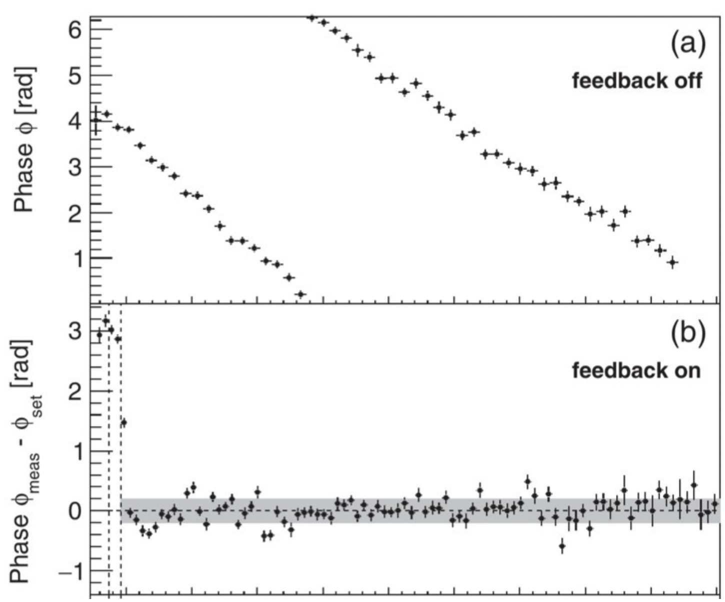
Feedback: the basic workflow:



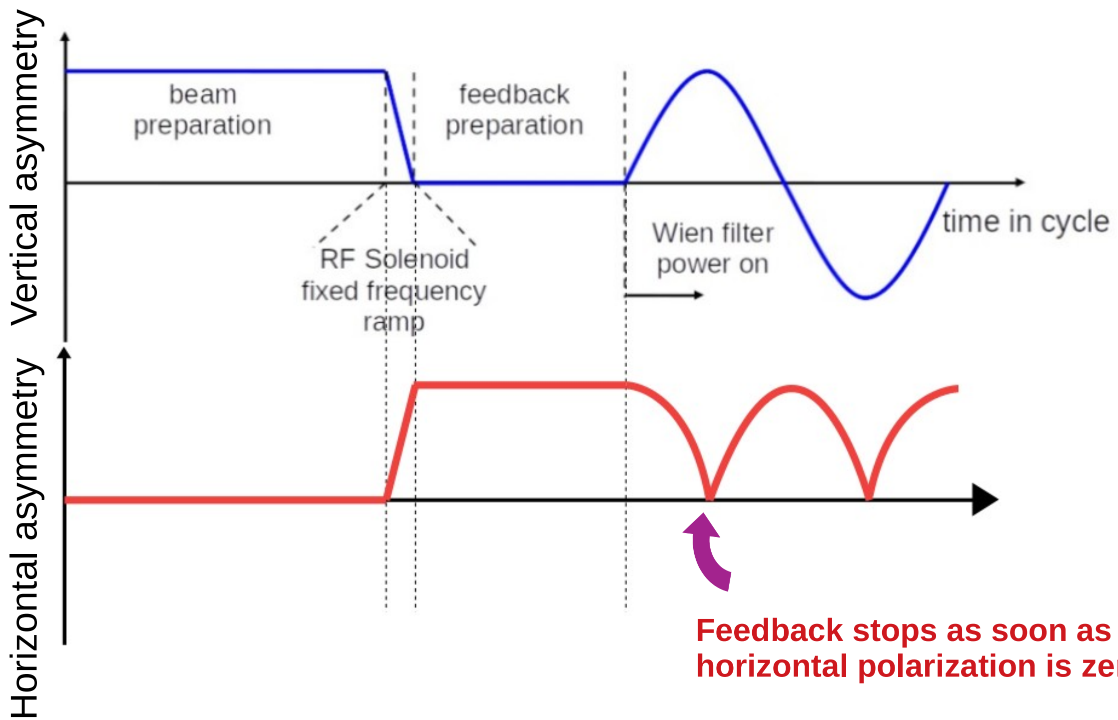
PRINCIPLE OF MEASUREMENTS

- Feedback monitors spin precession phase and adjust WF frequency to maintain the relative phase between spin precession and Wien filter

- Adjustment uncertainty of 0.2 rad



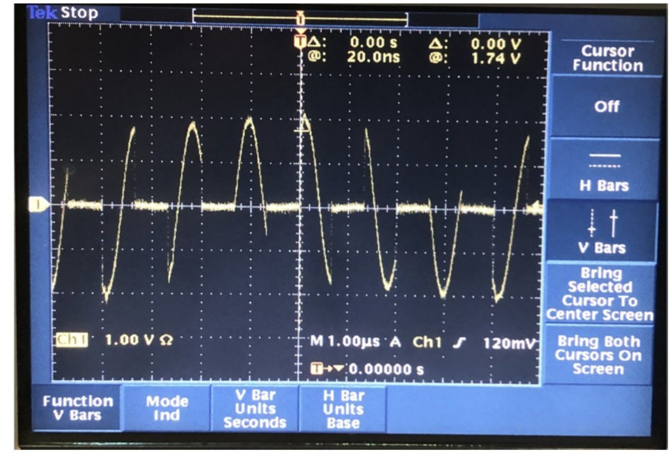
Feedback: the basic workflow

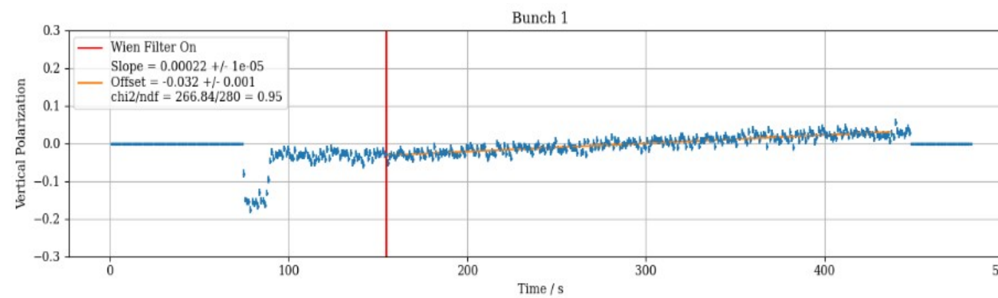


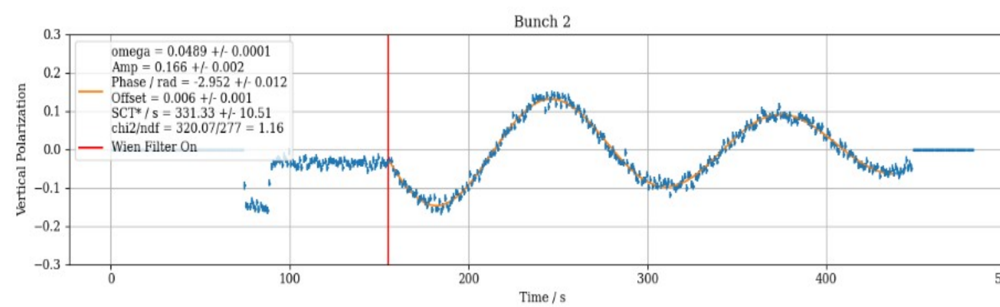
Feedback stops as soon as horizontal polarization is zero

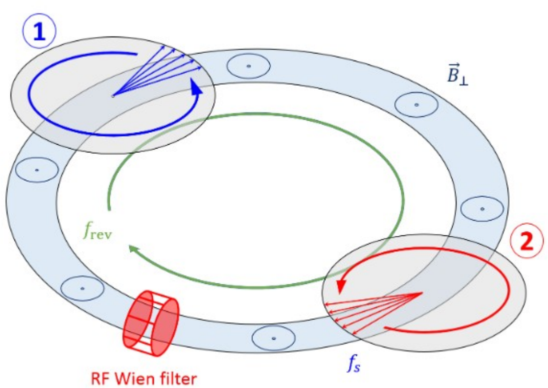
SELECTED BUNCH MANIPULATION

- Two bunches are stored in the ring
- In order to manipulate spin of one selected bunch, six high-speed RF switches were installed to gate the WF power for one of two bunches
- Capable of short switch time ~ few ns
- Bunch ② gets the RF Wien filter power and oscillate
- Bunch ① is used for phase locking with feedback system



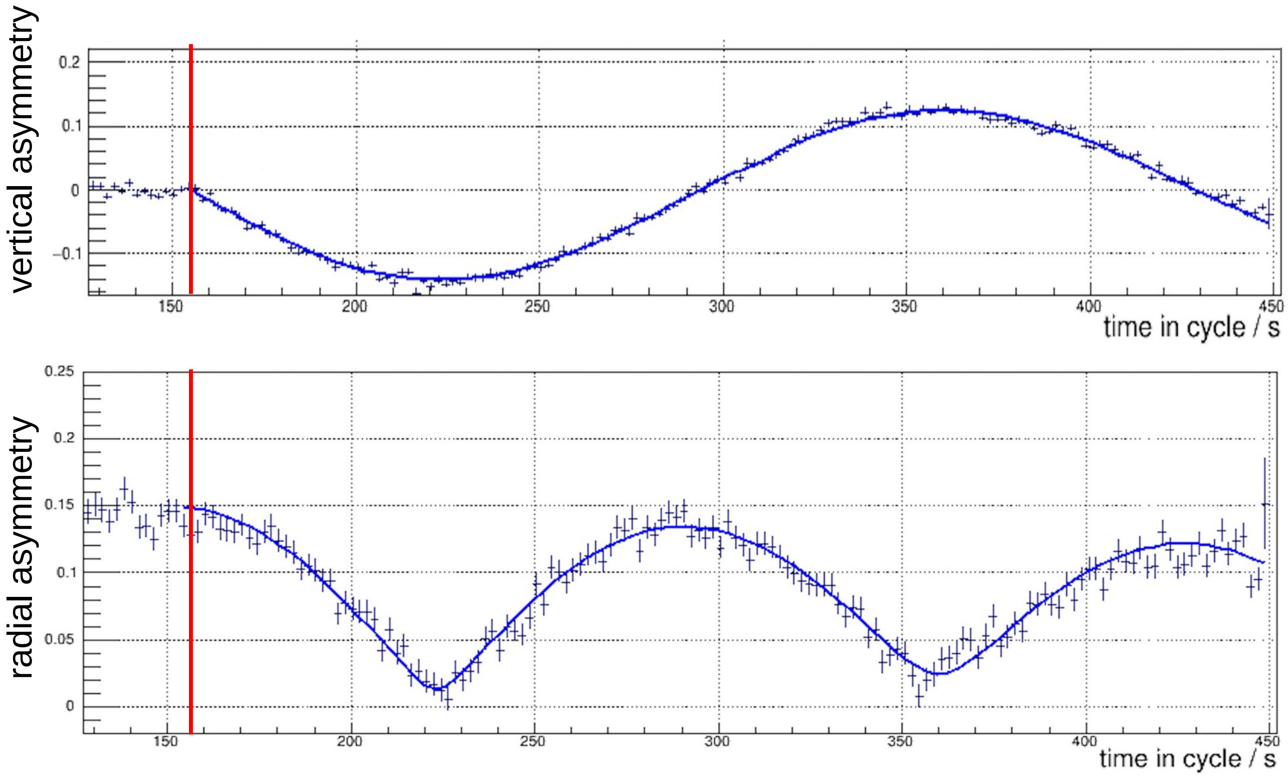






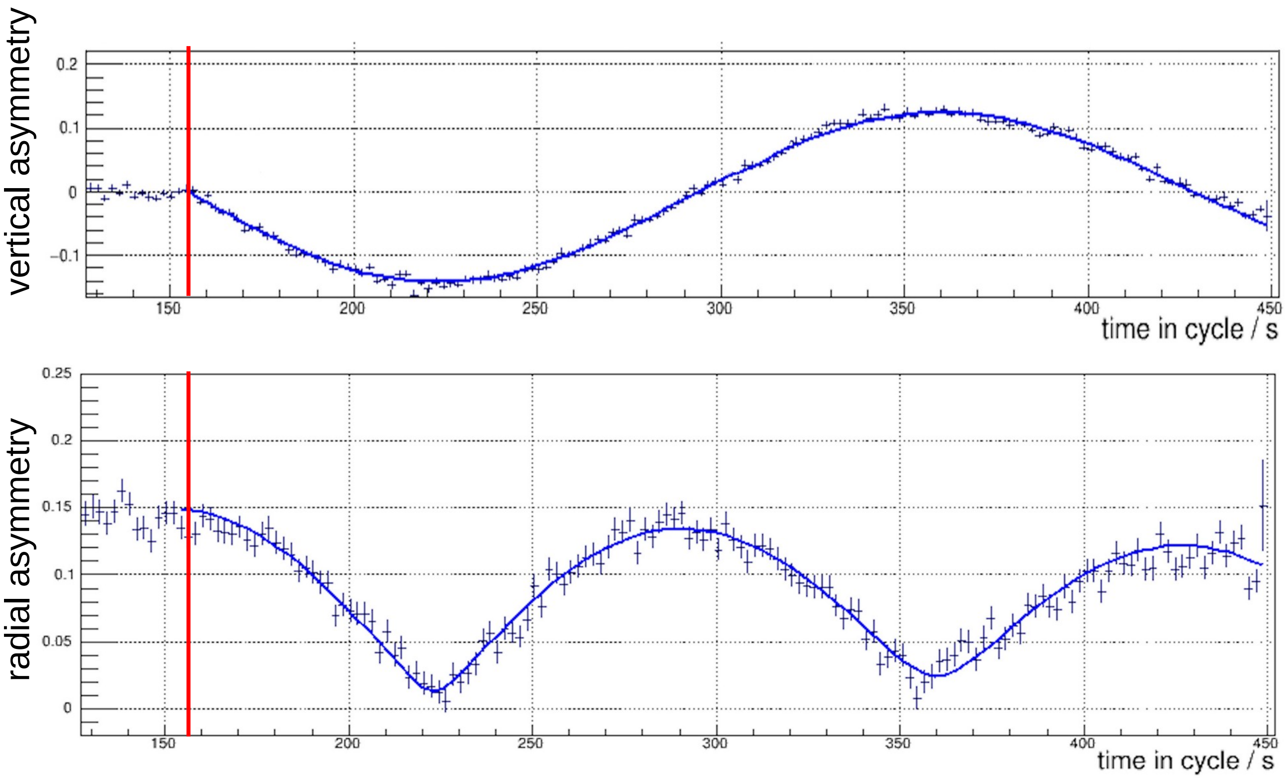
J. Slim, N.N. Nikolaev, and F. Rathmann, et al., Pilot bunch and co-magnetometry of polarized particles stored in a ring arXiv:2309.06561

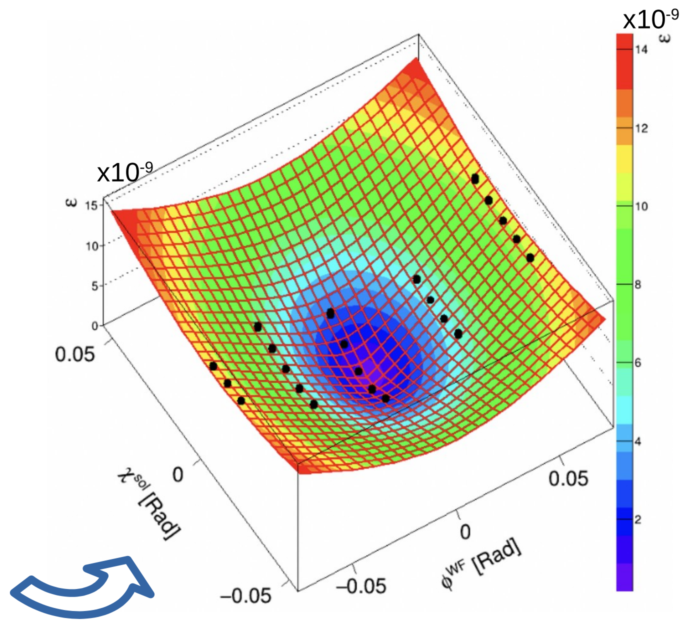
POLARIZATION OUT-OF PLANE OSCILLATION



- Both vertical and horizontal asymmetries dependencies for each Wien filter and snake setting were fit together in a combined fit.
- For horizontal asymmetry only absolute value is available
- Spin oscillation frequency depending on the Wien filter and snake settings is going to the resonance strength map

POLARIZATION OUT-OF PLANE OSCILLATION





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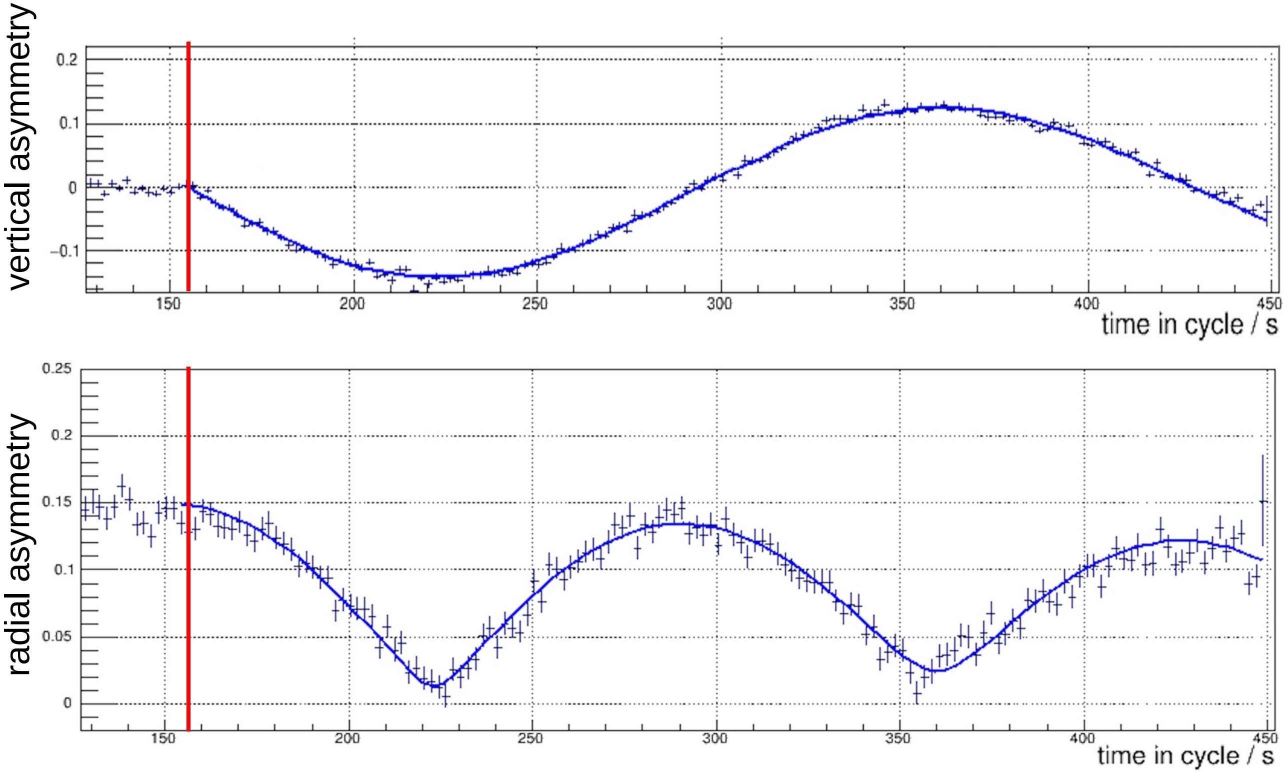

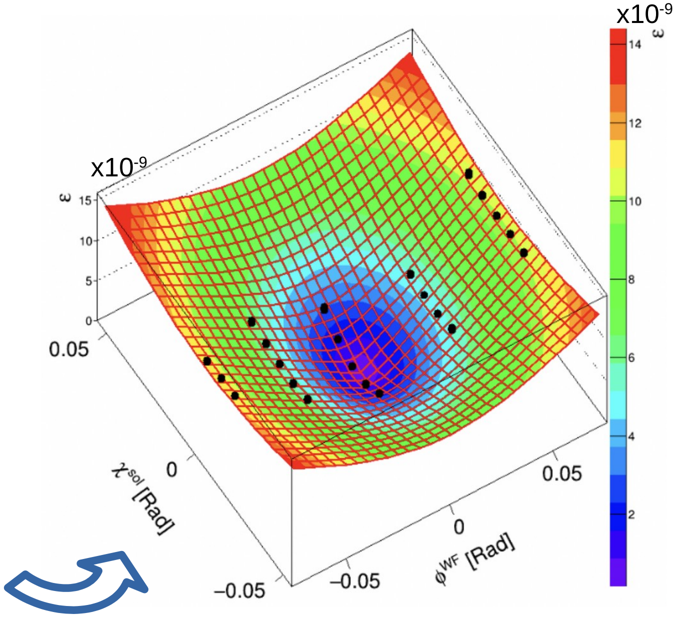

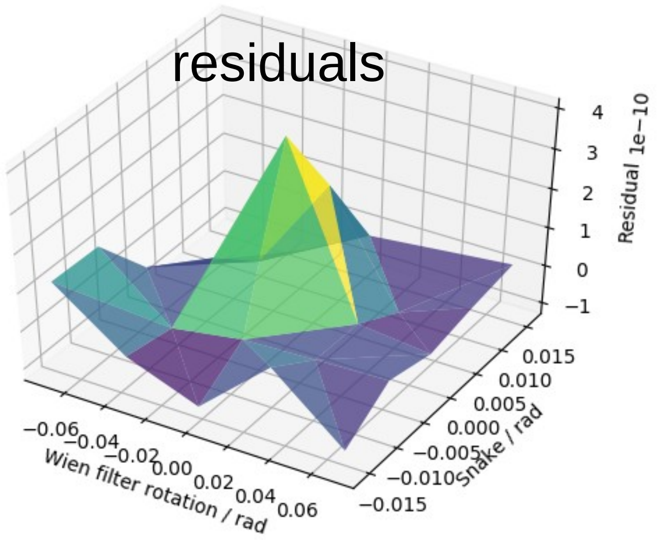

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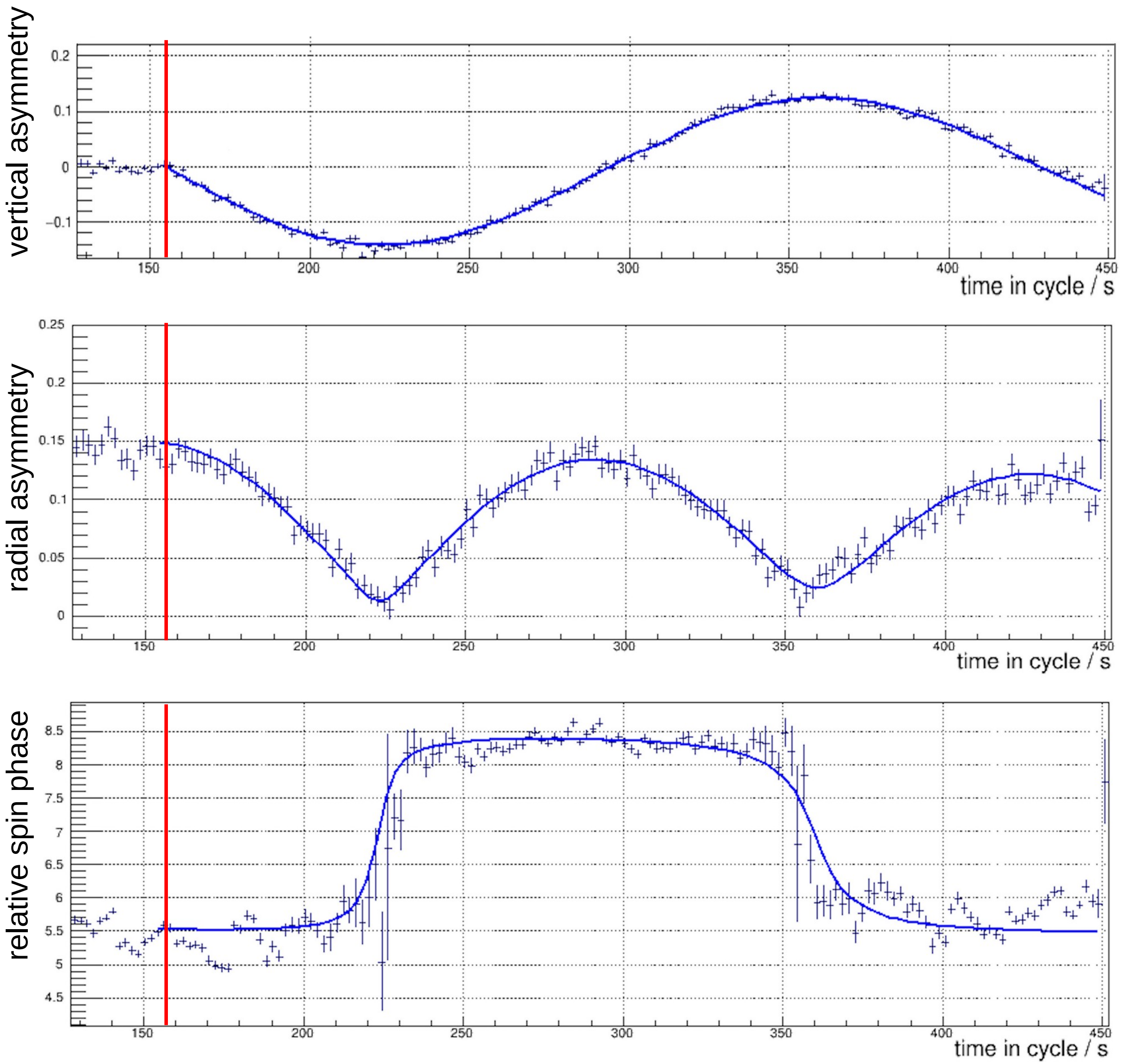
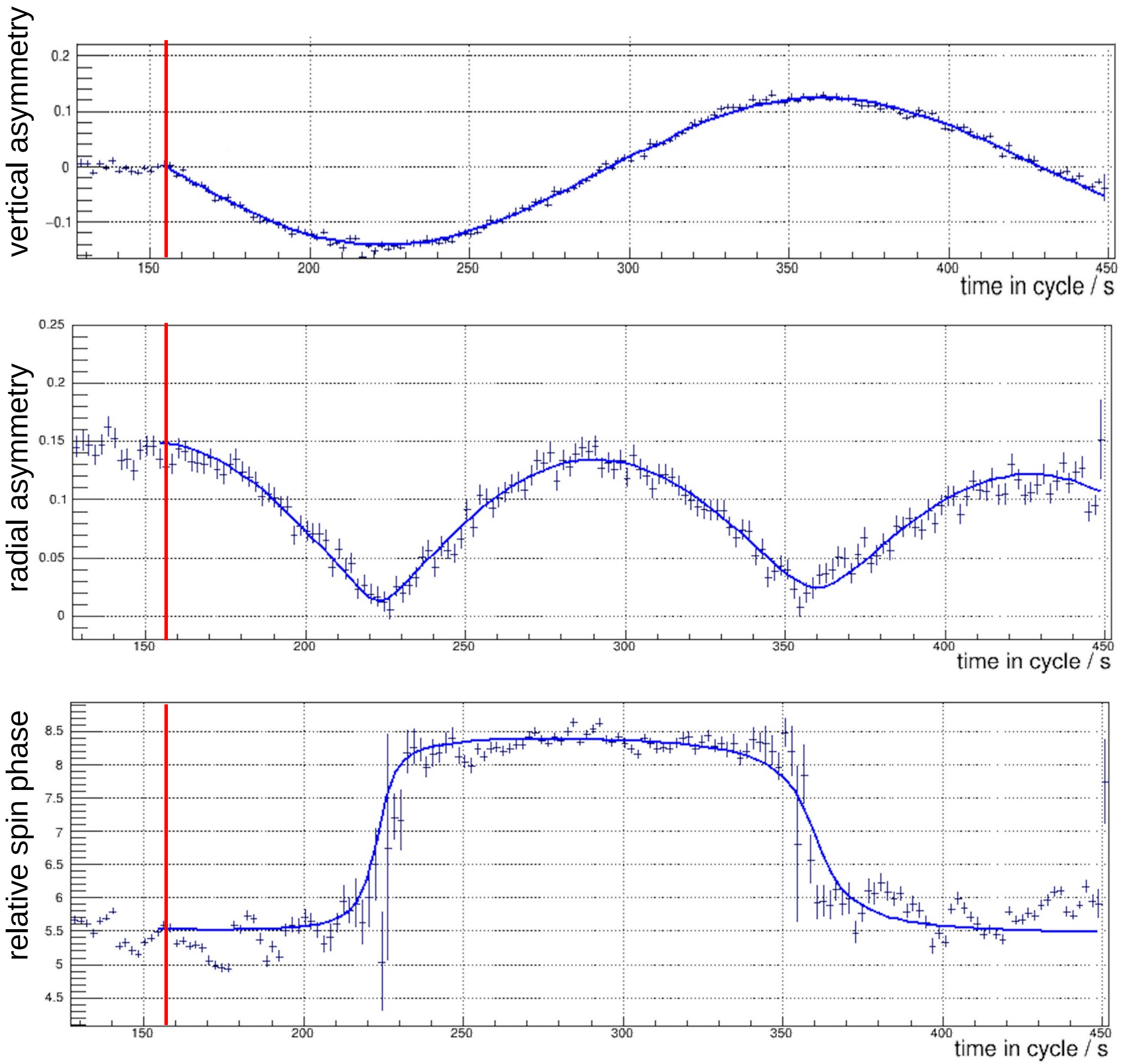
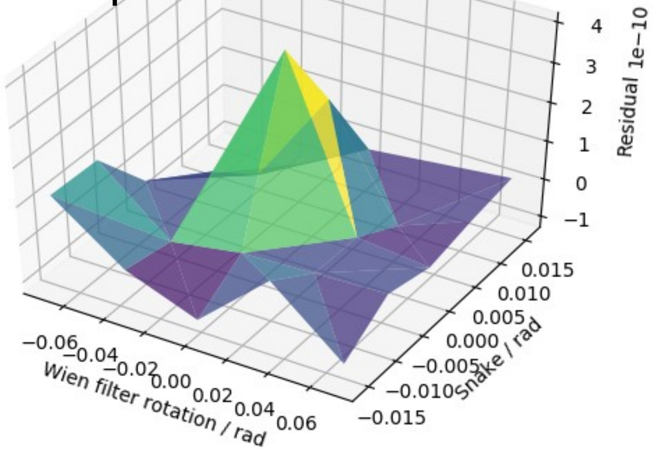


- Both vertical and horizontal asymmetries dependencies as well as a phase dependencies for each Wien filter and snake setting were fit together in a combined fit.
- For horizontal asymmetry only absolute value is available.
- Spin oscillation frequency depending on the Wien filter and snake settings is going to the resonance strength map.
- Including all three dependencies in the combined fit increases the accuracy of the results.

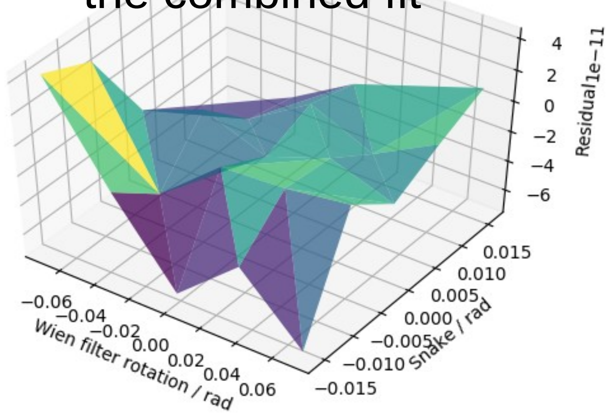
POLARIZATION OUT-OF PLANE OSCILLATION



Residuals without phases in the fit



Residuals with phases included in the combined fit



RESONANCE STRENGTH MAP

Parametric resonance strength defined as:

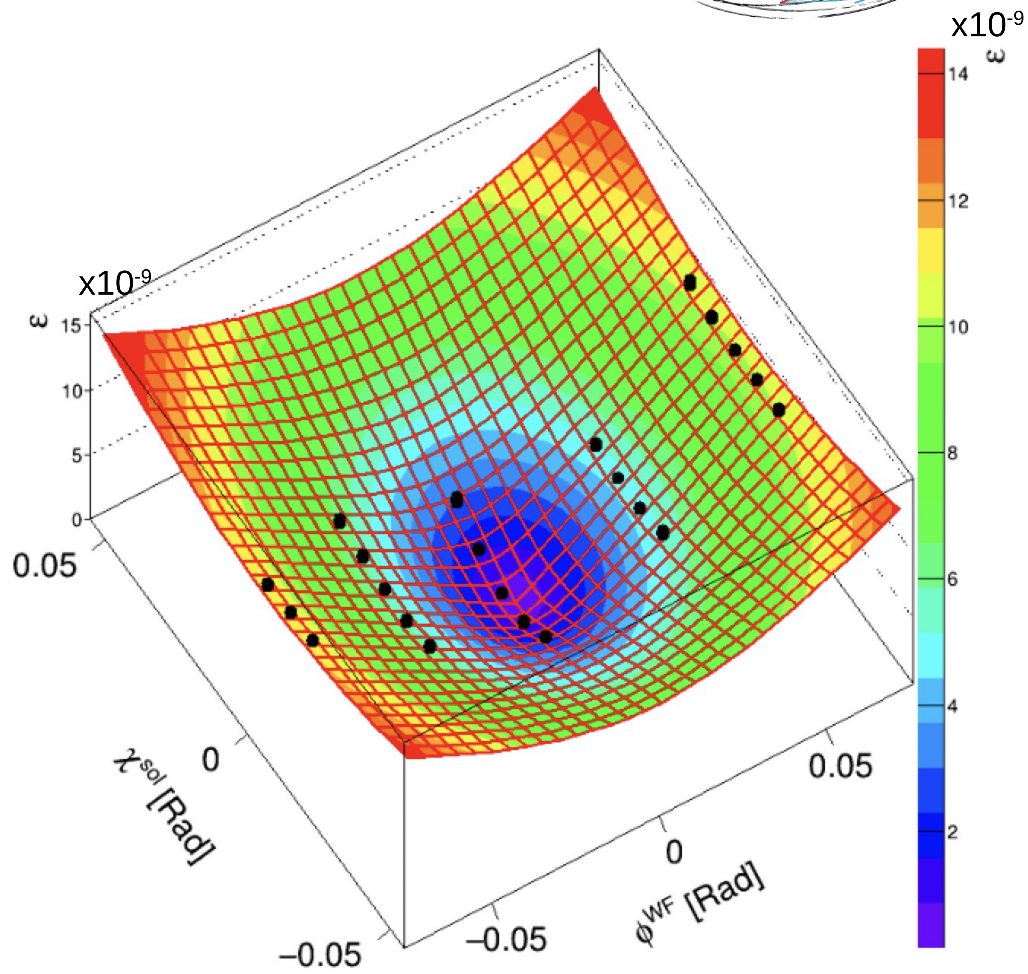
$$\varepsilon^{EDM} = \frac{\Omega^{P_y}}{\Omega^{rev}}$$

Minimum of the surface shows orientation of invariant spin axis:

φ_0^{wf} = 2.51 ± 0.04 mrad

X_0^{sol} = -3.93 ± 0.06 mrad

Orientation of precession axis without EDM will come out of spin tracking calculations



$$\varepsilon = \frac{\chi_{WF}}{4\pi}\sqrt{\left(A_{WF}^2(\phi_0^{WF}-\phi^{WF})^2 + A_{Sol}^2\left(\frac{\chi_0^{sol}}{2\sin(\pi\nu_s)}-\chi^{sol}\right)^2\right)} + \varepsilon_0$$

SUMMARY AND OUTLOOK

- Charged hadron EDMs: Possibility to find sources of CP violation and to explain matter-antimatter asymmetry in the universe.
- Precursor experiments performed as a proof-of-principle of EDM measurement at storage rings.
- New method of manipulating the polarization of the selected bunch out of two bunches in the ring was developed and performed.
- CERN Yellow Report prepared by CPEDM collaboration.
  F. Abusaif et al., “Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study,” 2020 https://arxiv.org/abs/1912.07881
- Work on Design Report for PTR ongoing.
- See Frank Rathmann’s talk for more information on JEDI program, Thursday 18:00