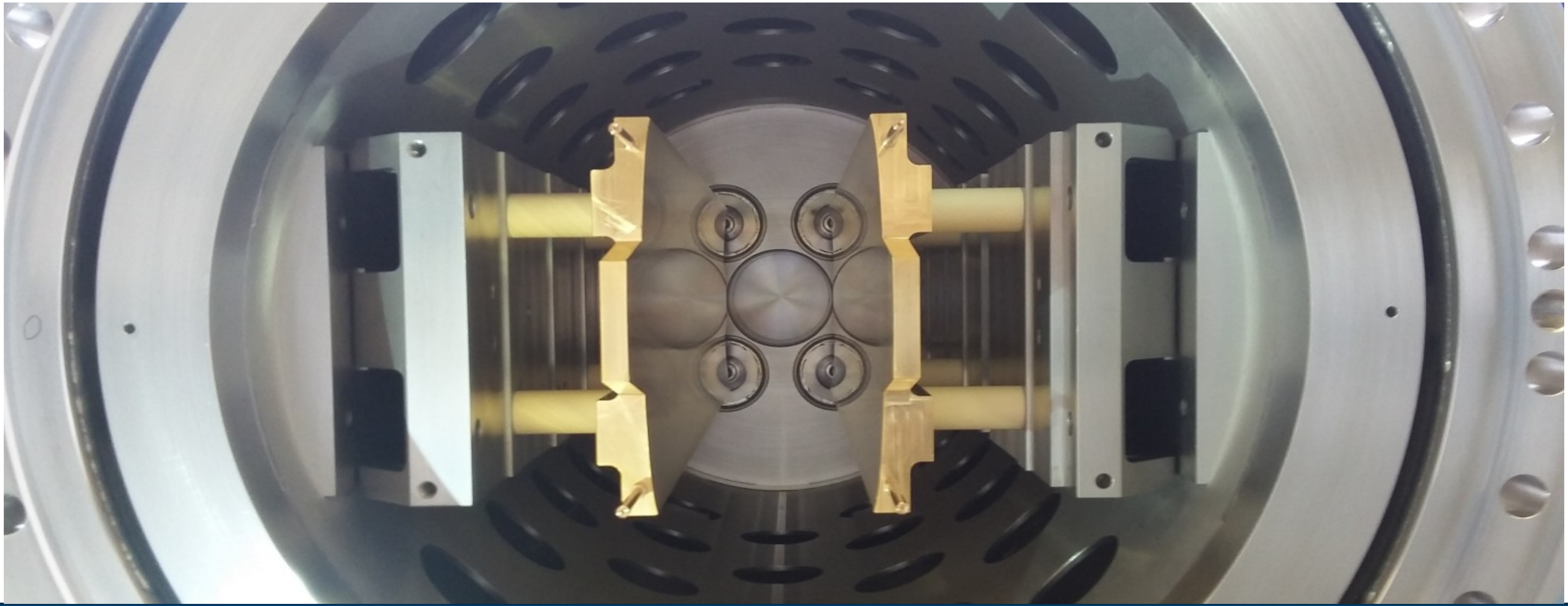


THE SEARCH FOR ELECTRIC DIPOLE MOMENT OF CHARGED PARTICLES USING STORAGE RING COSY

PSTP'22 Mainz 30.09.2022 Vera Shmakova for the JEDI Collaboration

JEDI

Università degli Studi di Ferrara

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)

***CP* violation**

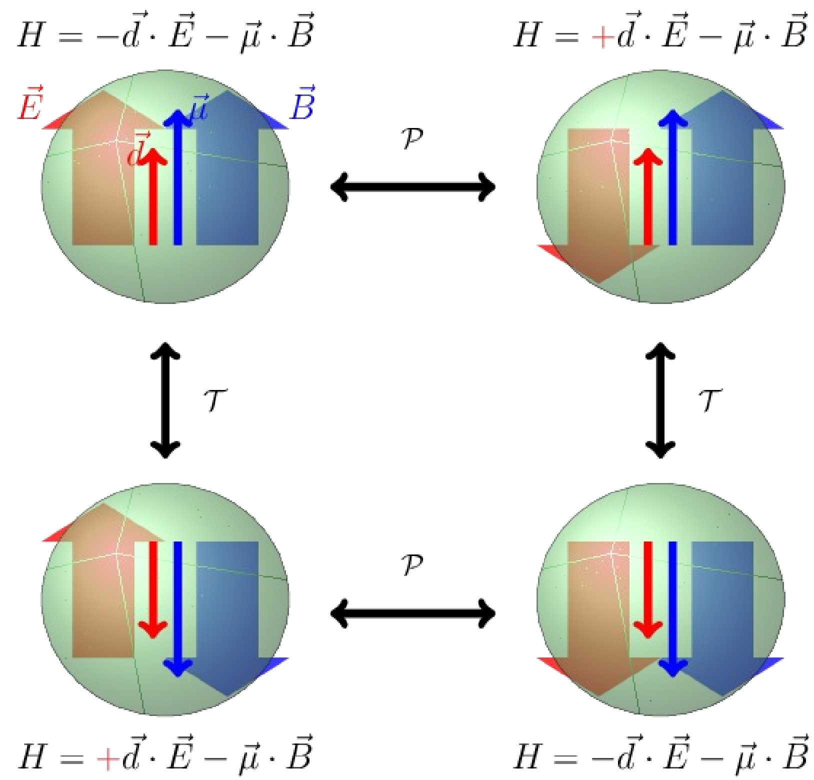
- *CP* violation in SM is not sufficient

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



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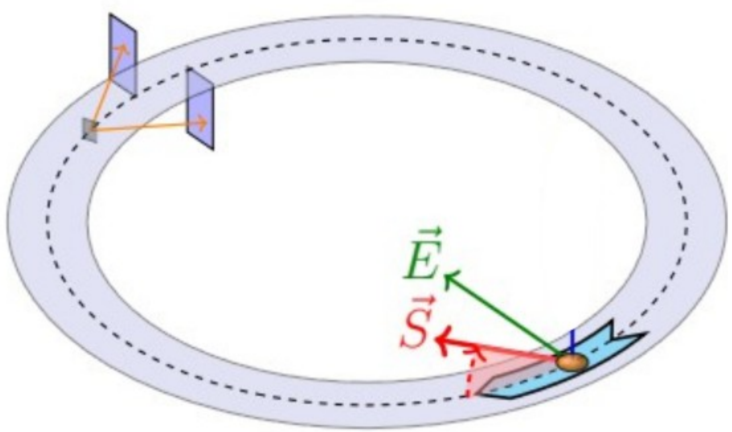
$$\vec{\Omega}_{EDM} = -\frac{\eta q}{2mc}\{\vec{E} + c\,\cancel{\vec{\beta}\times\vec{B}}\}$$

“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

PRESTO

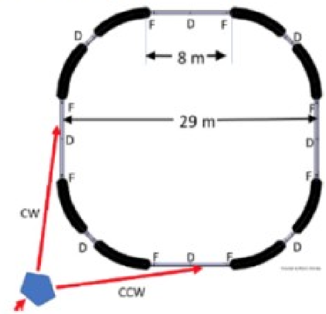
Stage 1

- precursor experiment

pure magnetic ring

Stage 2

- prototype ring



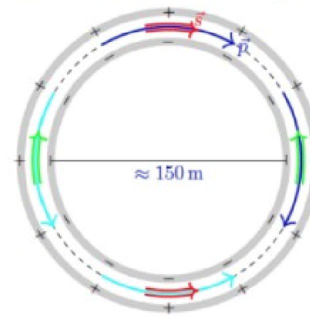
combined E/B ring

simultaneous CW-CCW beams

frozen spin

Stage 3

- dedicated storage ring



all electric proton ring

simultaneous CW-CCW beams

frozen spin

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

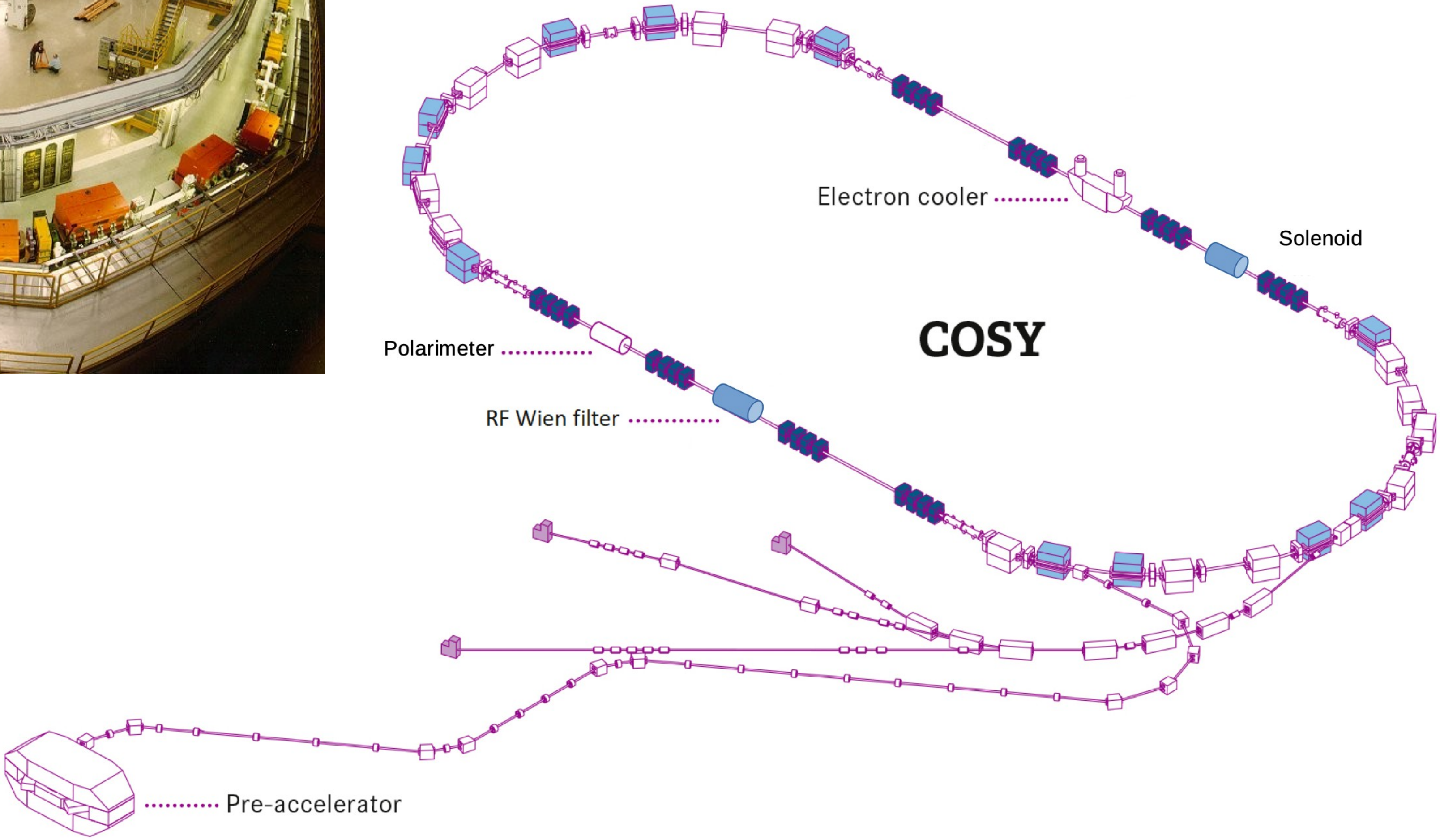
10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21} 10^{-22} 10^{-23} 10^{-24} 10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29}

* 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

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

MDM causes fast spin precession in horizontal plane

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

⇩

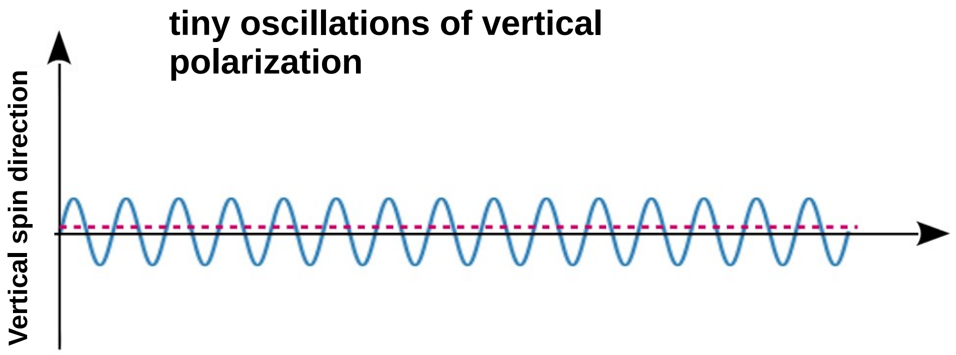
access to EDM

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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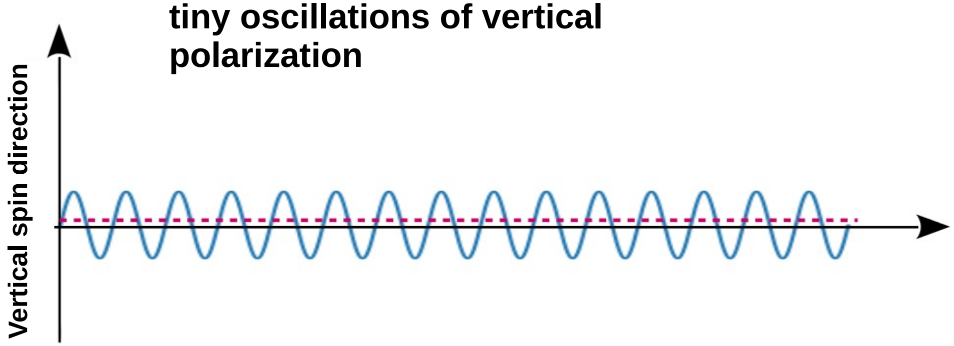
⇩

no accumulation of vertical asymmetry

tiny oscillations of vertical polarization

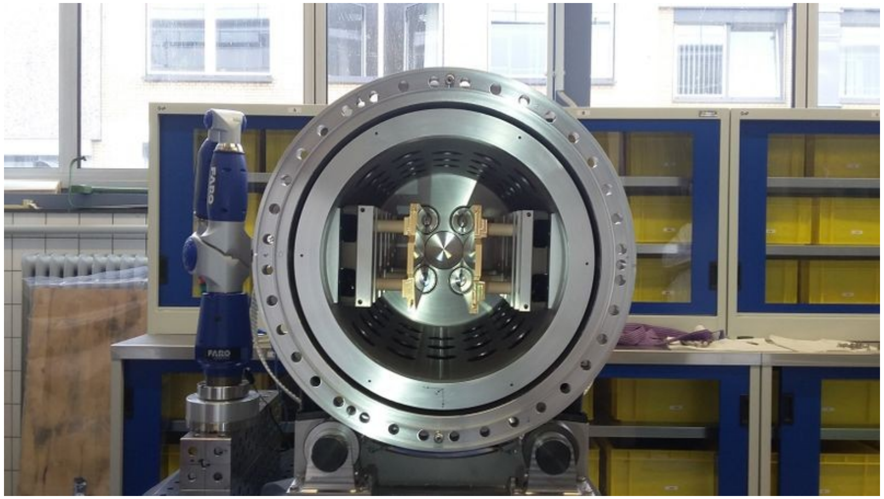


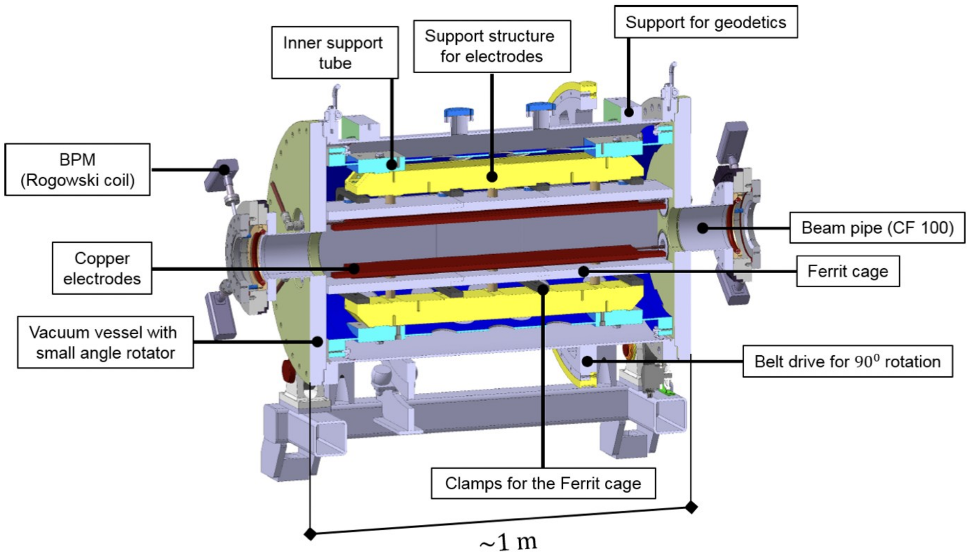
RF Wien filter

*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 $\vec{E} = (E_x, 0, 0)$





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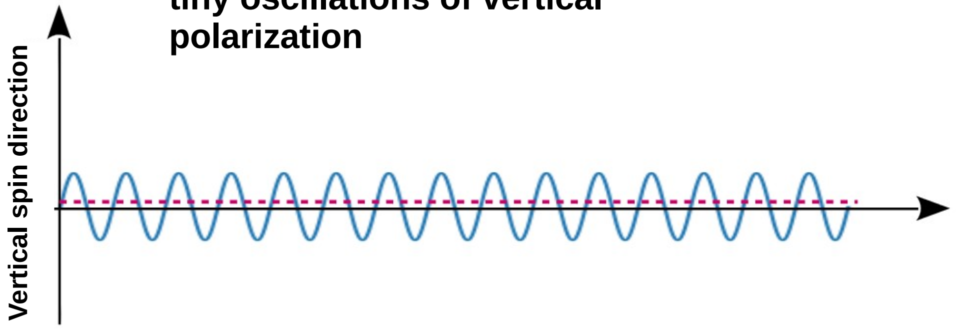

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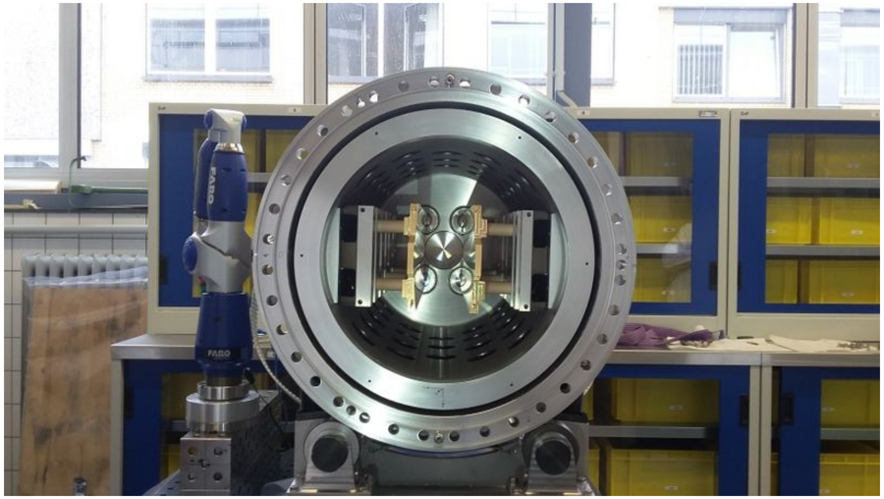
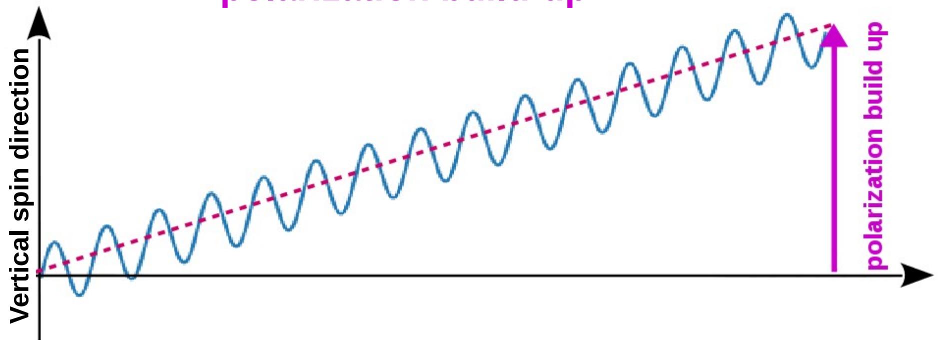


phase lock between spin precession and RF Wien filter

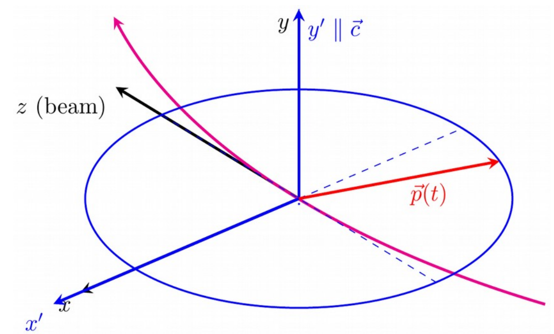
⇩

polarization build-up

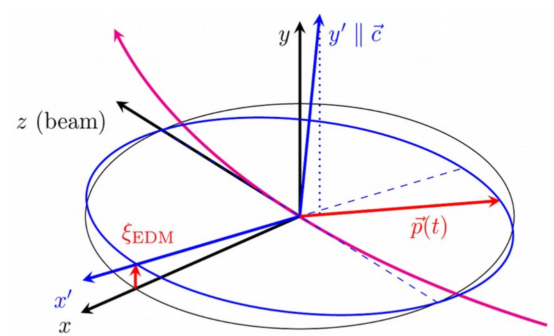


EFFECT ON INVARIANT SPIN AXIS

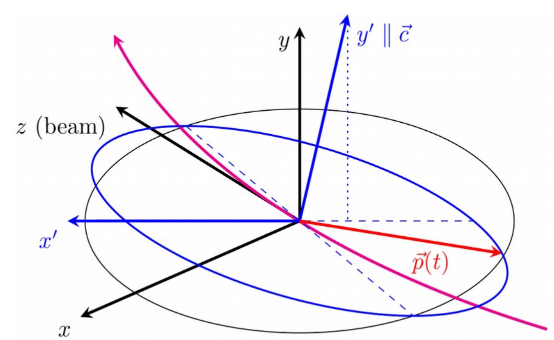
EDM absent



Pure EDM effect

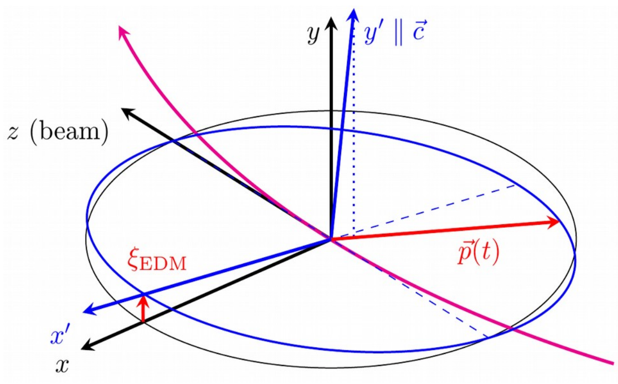


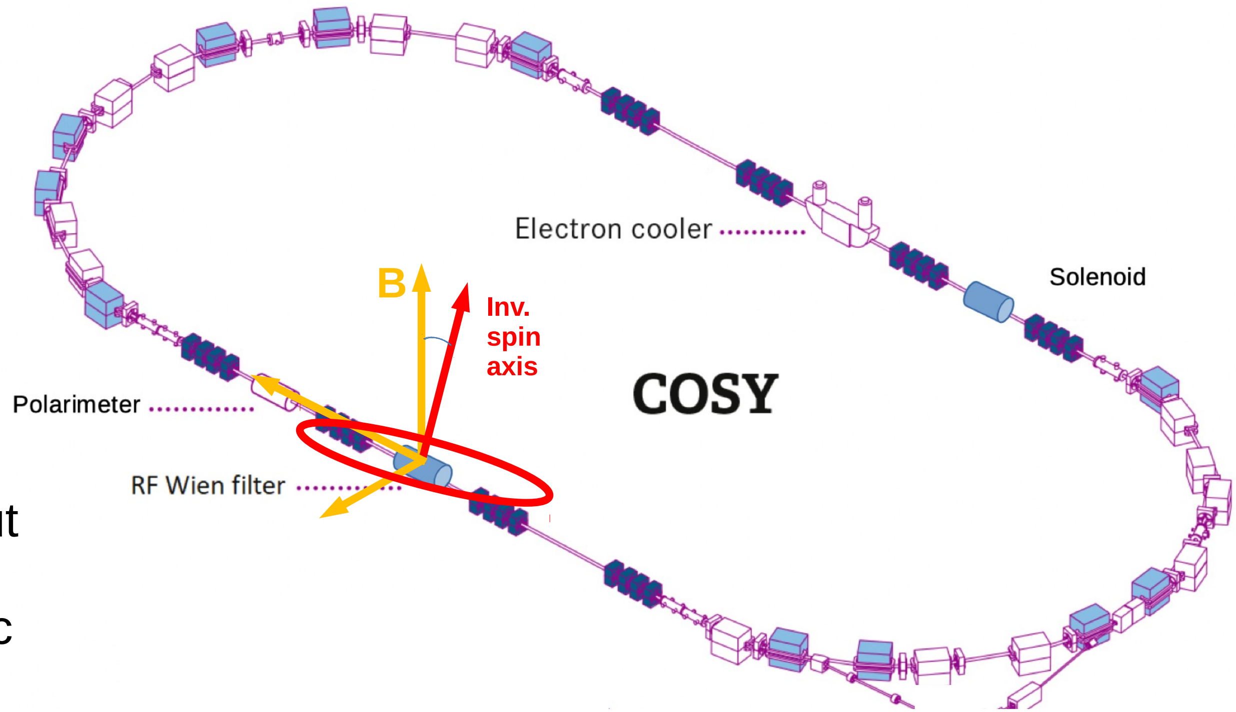
EDM + magnetic misalignments



MEASUREMENT OF THE EDM EFFECT

How the EDM effect actually measured:





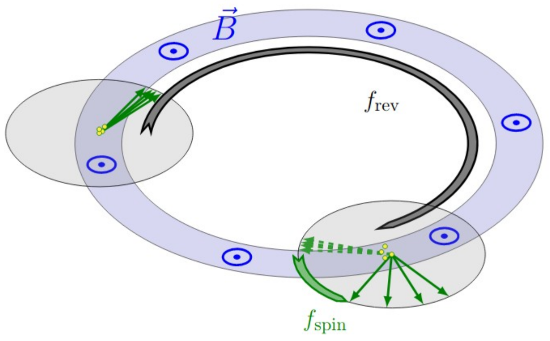
- The RF Wien filter is rotated about beam axis:
    - it generates radial magnetic field, which allows to compensate to radial tilt of invariant spin axis

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

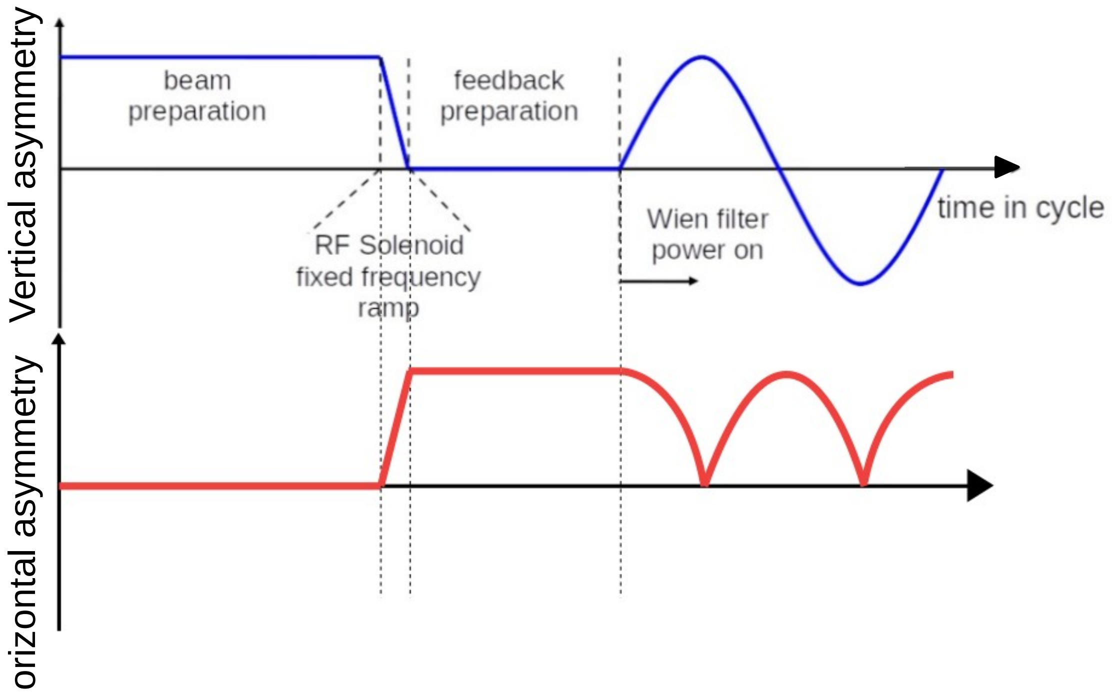
PRINCIPLE OF MEASUREMENTS

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

- SCT > 1000 s.



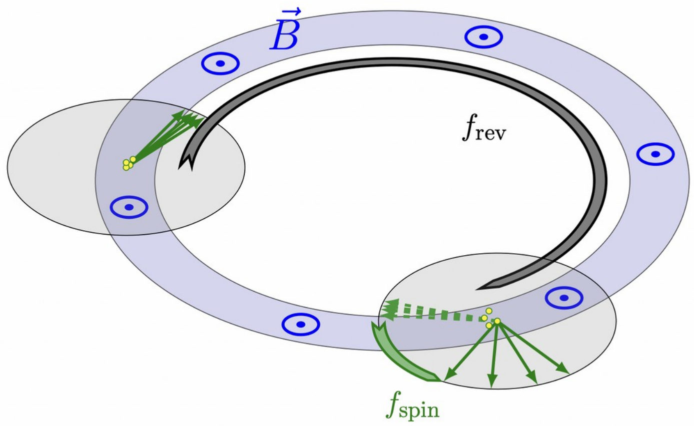
Feedback: the basic workflow:

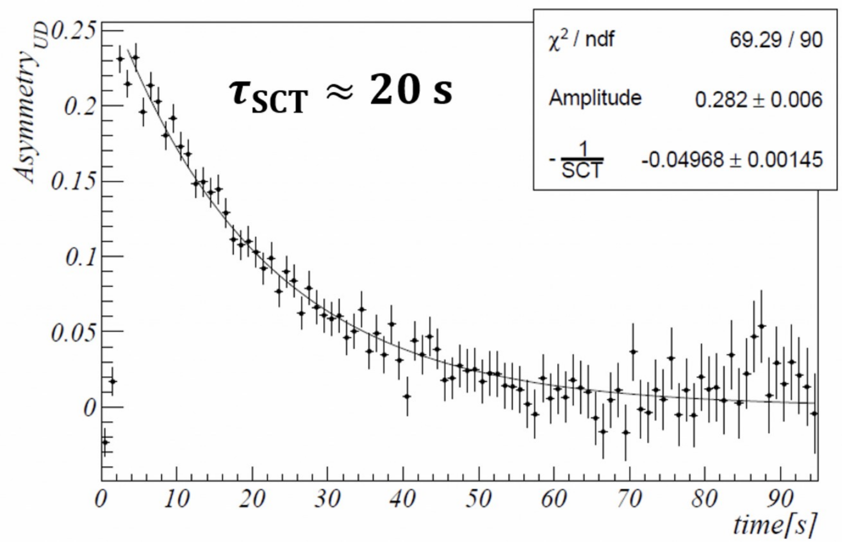


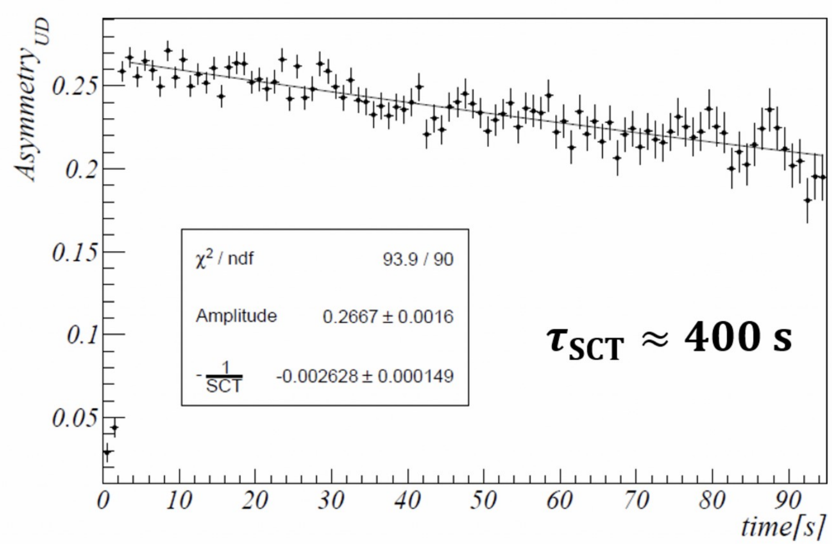
SPIN COHERENCE TIME

For long SCT:

- Beam bunching
- Cooling
- Correction with sextupole magnets







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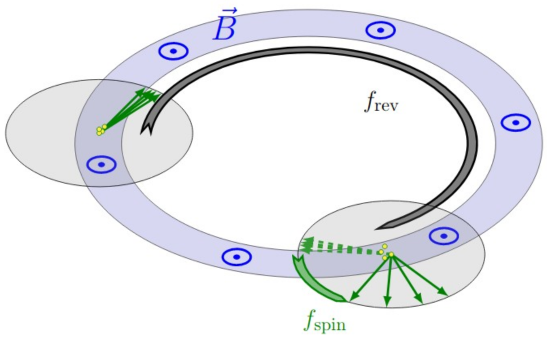
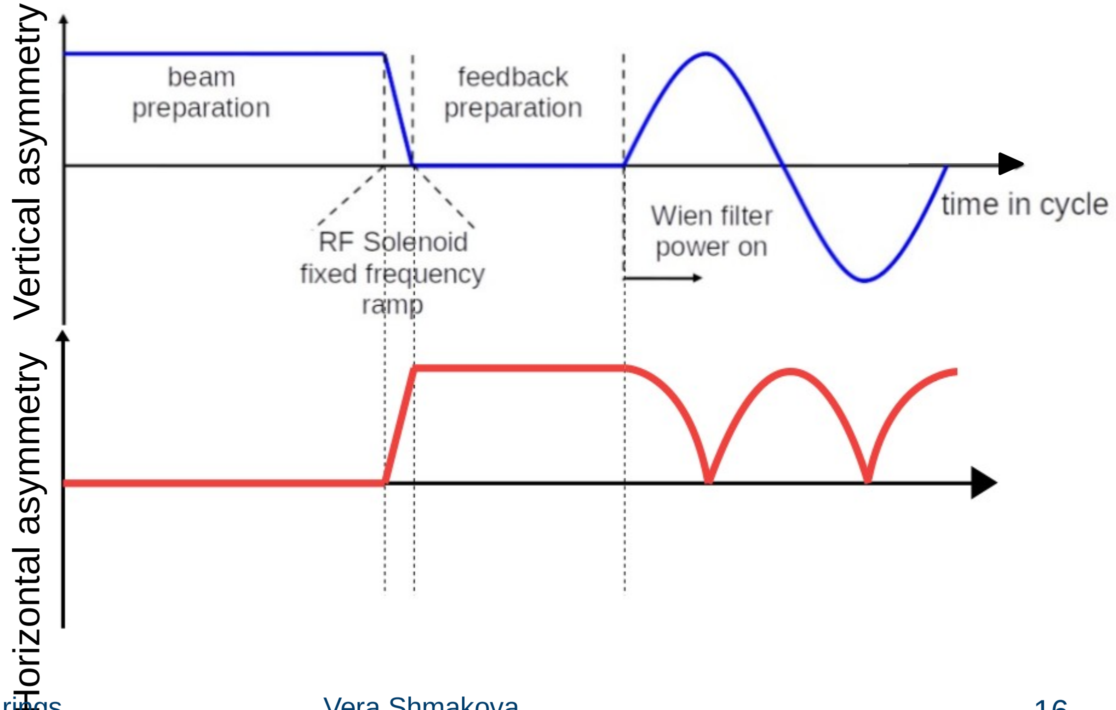


- Spin precesses with 120 kHz.

- Wien filter operates on resonance:
  $f = f_{COSY} + f_{spin\ pres} = 871.430$ kHz

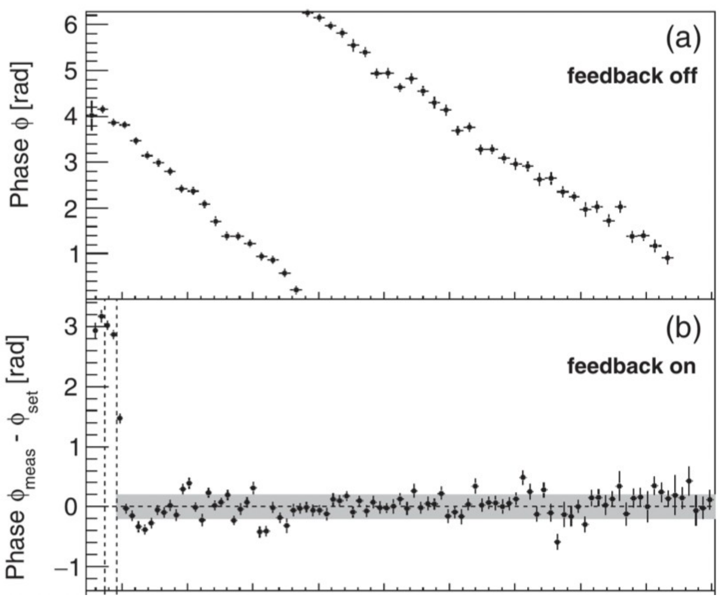
- Phase lock between spin precession and Wien filter

Feedback: the basic workflow:

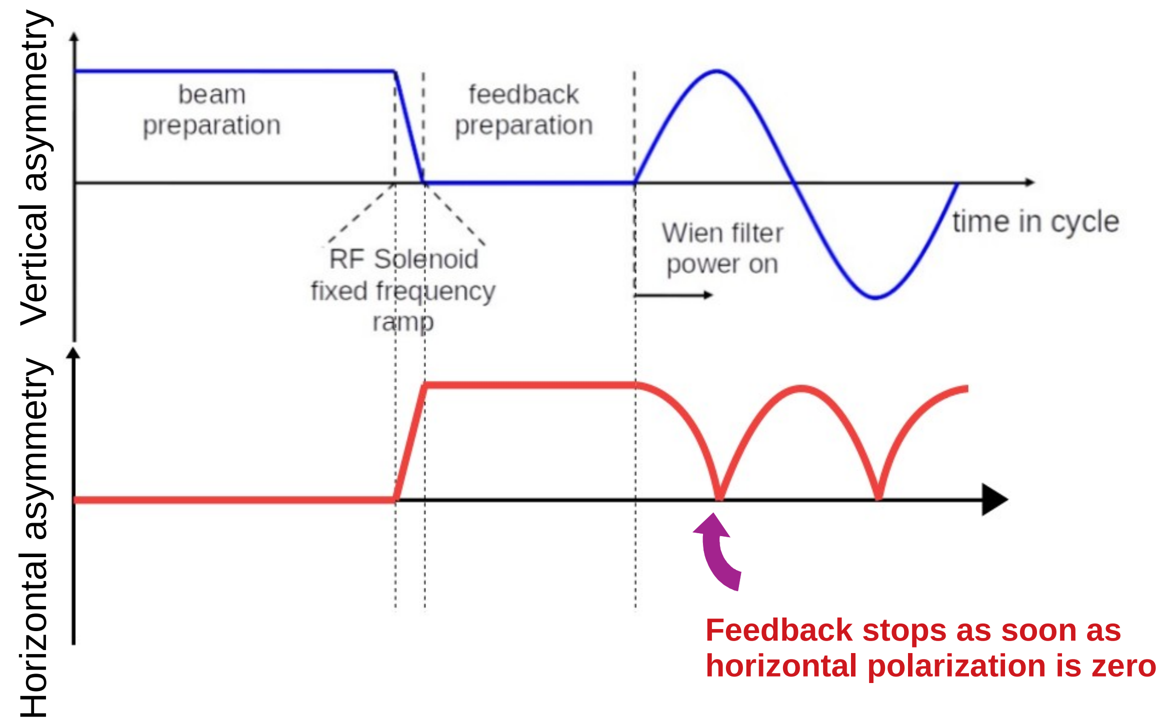


PRINCIPLE OF MEASUREMENTS

- 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



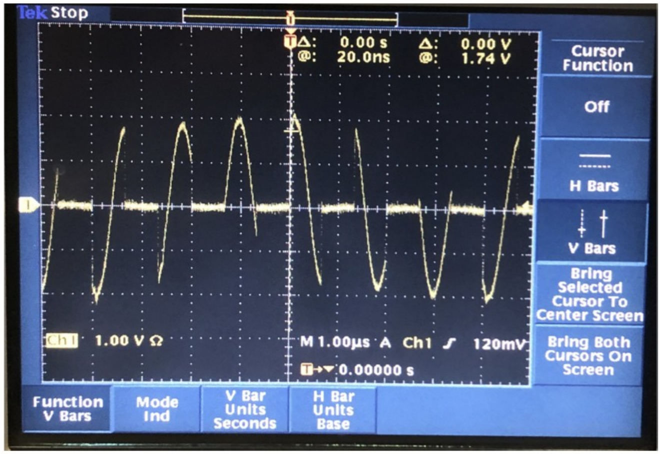
Feedback: the basic workflow

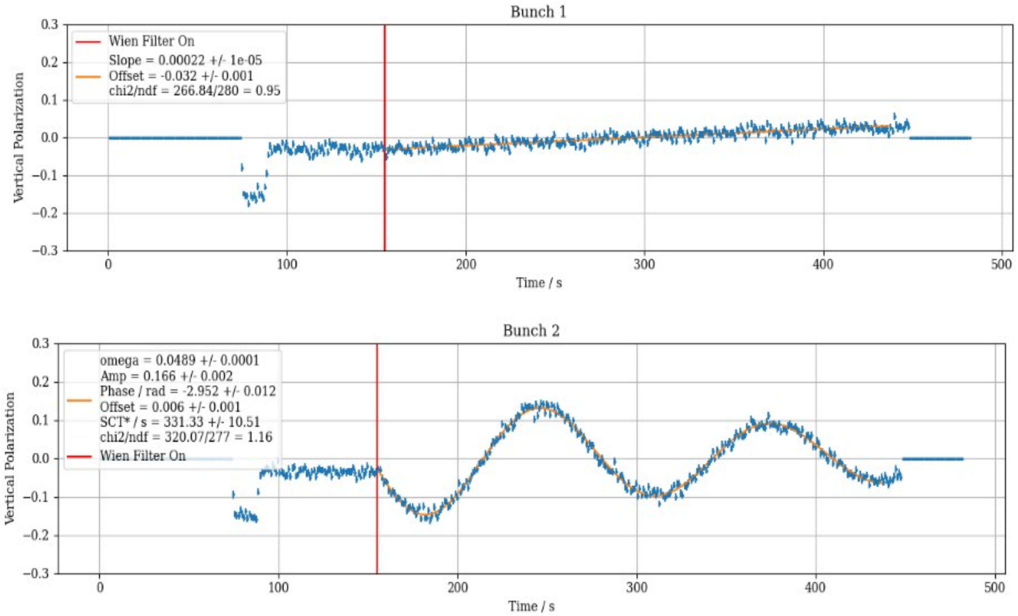


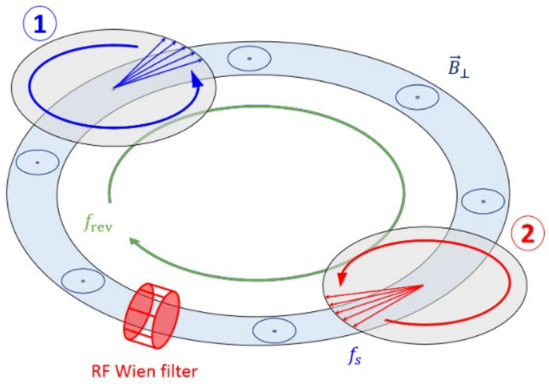
RF SWITCHES

Rotating the spin of one bunch out of the two in the ring:

- 8 high-speed RF switches to gate the WF power for one of two bunches
- Capable of short switch time ~ few ns
- Bunch ② feels the power and oscillate
- Bunch ① is used as pilot bunch
- for phase locking



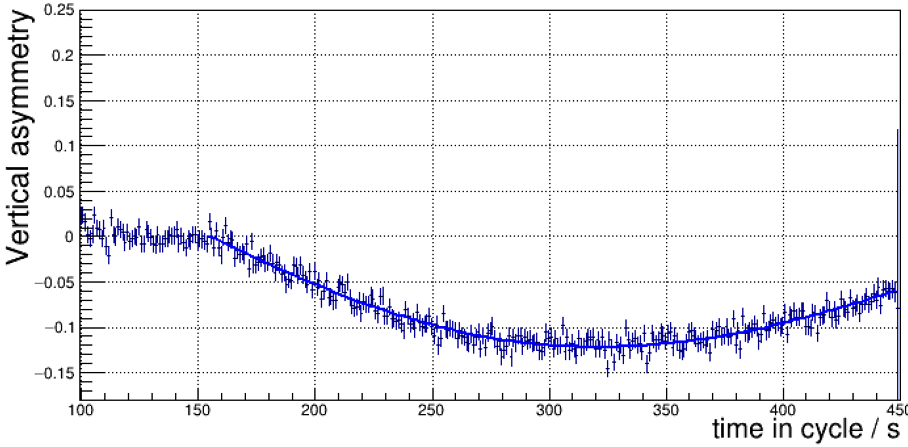


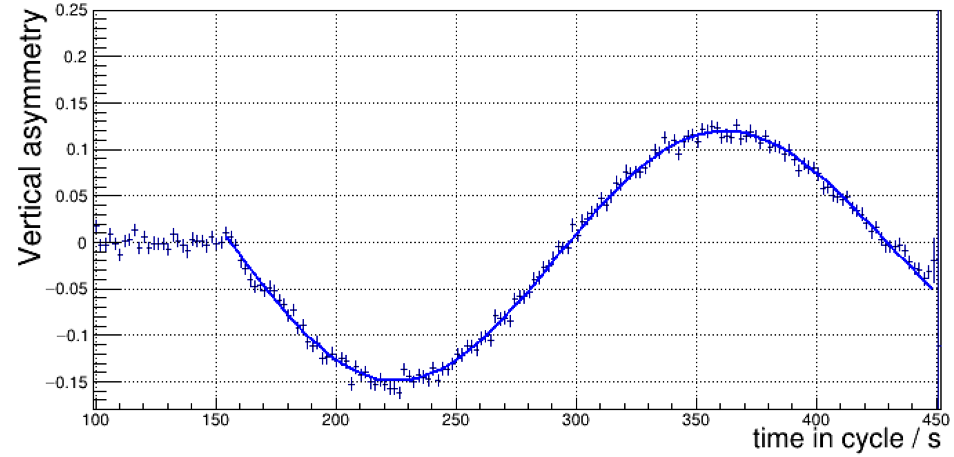


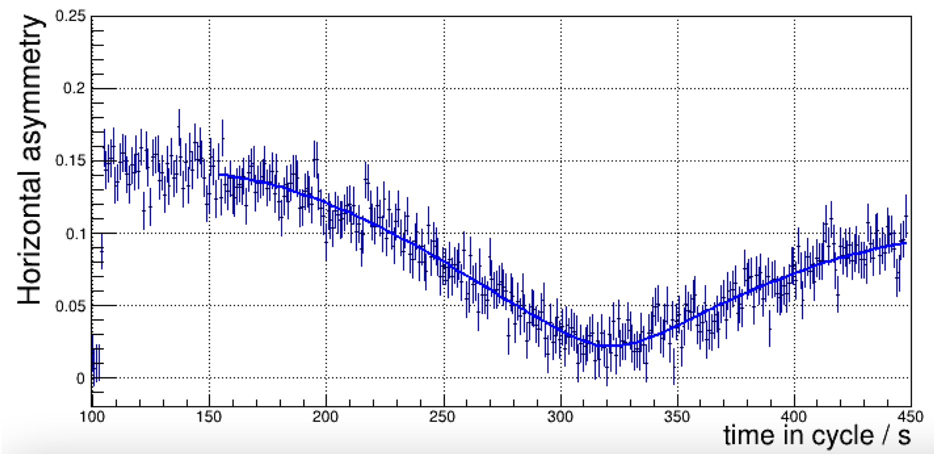
POLARIZATION OUT-OF PLANE OSCILLATION

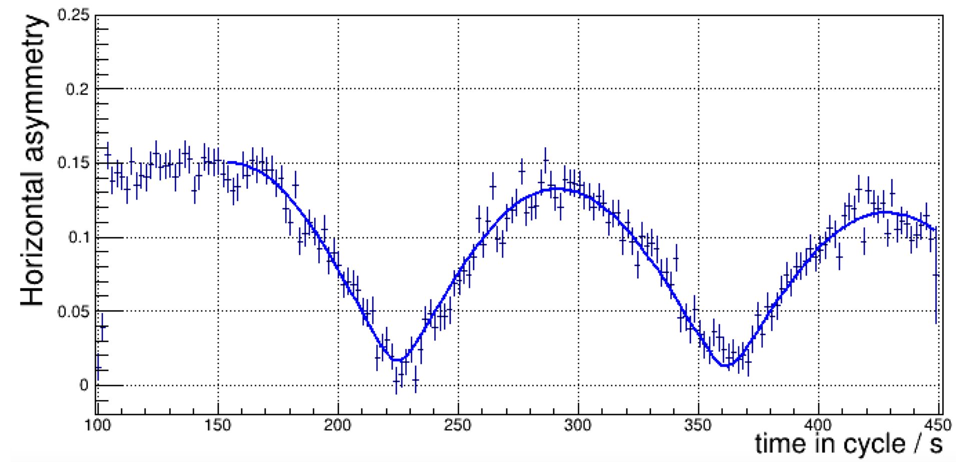
WF @ 0
Solenoid @ -4 A

WF @ 2 Deg
Solenoid @ 0 A









RESULTS

Parametric resonance strength defined as:

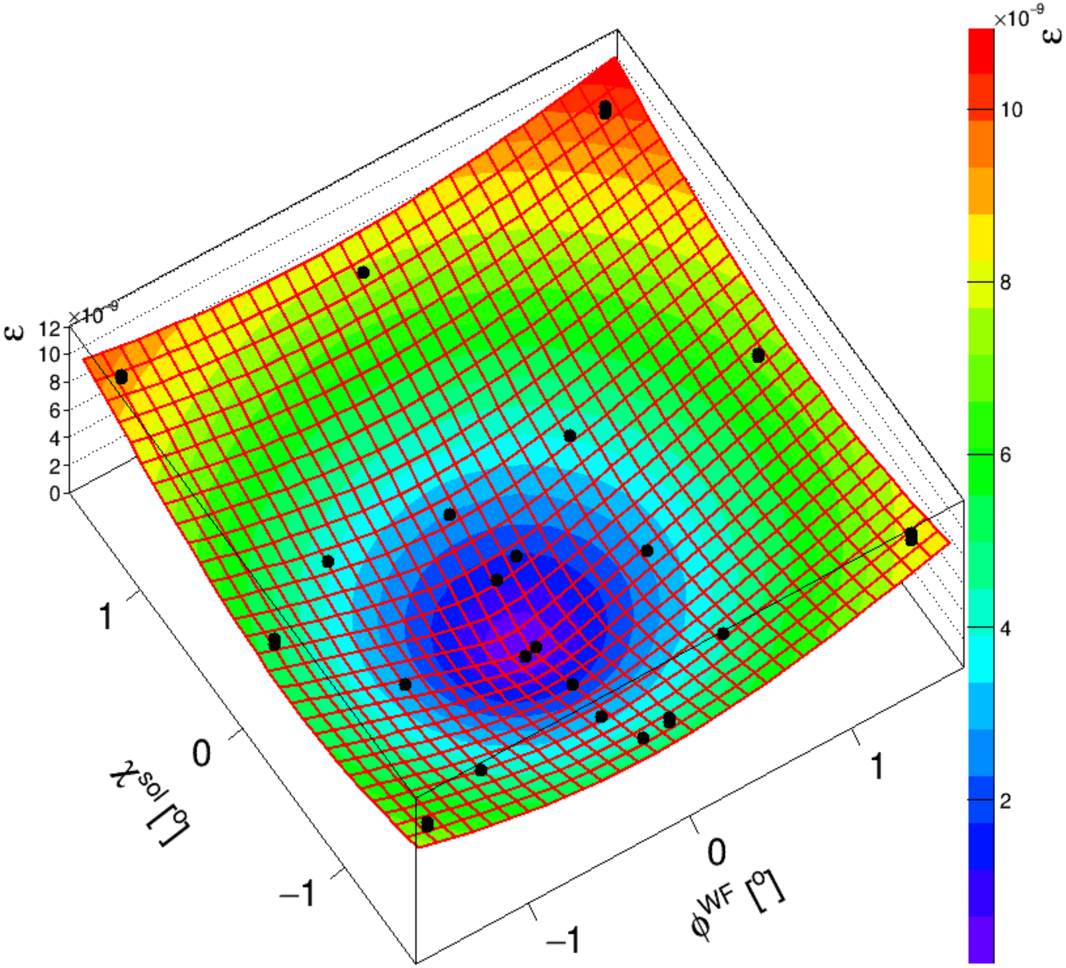
$$\varepsilon^{EDM} = \frac{\Omega^{P_y}}{\Omega^{rev}}$$

Minimum of the surface shows orientation of invariant spin axis:

φ_0^{wf} = 3.42 +- 0.06 mrad

X_0^{sol} = 5.26 +- 0.04 mrad

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



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

SUMMARY

- 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 managing the polarization for one 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. Proposal PRESTO is out.
- COSY remains a unique facility for such studies.

LIST OF IMPROVEMENTS

- Alignment campaigns of COSY magnet system
- Beam-based alignment
  PhD thesis T. Wagner
- New tool for fast tune and chromaticity measurement
  P. Niedermayer and B. Breitkeutz
- Slow control system
  I. Bekman and IKP4
- COSY signals and distribution was improved
  K. Laihem
- Rogowski coils at the Wien filter place
  F. Abusaif, R.Suvarna
- New JEDI polarimeter
  I. Keshelashvili and the polarimeter group
- 8 high-speed RF switchers to gate the WF power for one of the bunches
  pilot bunch technique
  J. Slim, A. Nass, F. Rathmann, G. Tagliente