THE SEARCH FOR ELECTRIC DIPOLE MOMENTS OF CHARGED PARTICLES USING STORAGE RINGS

INTERNATIONAL SPIN SYMPOSIUM - SPIN2021

19.10.2021

VERA SHMAKOVA FOR THE JEDI COLLABORATION

MATTER-ANTIMATTER ASYMMETRY

Why is our universe is matter dominated?

Big Bang produced same amount of matter – antimatter

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)*	$\frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-18}$

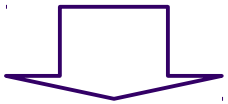
Preference of matter (A. Sakharov criteria, 1967)

***C*, *CP* violation**

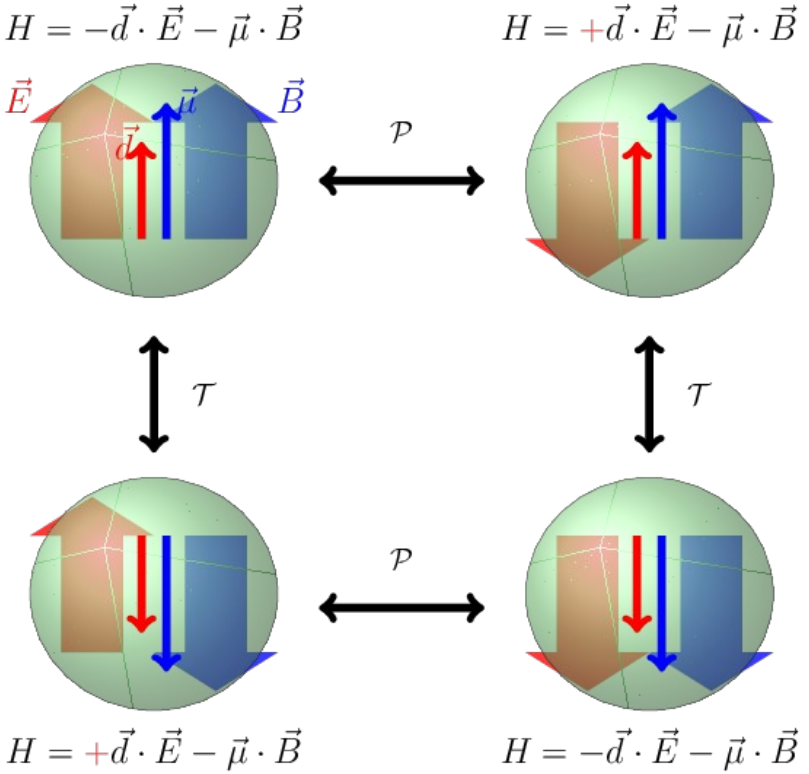
There is *CP* violation in SM, but not sufficiently large

ELECTRIC DIPOLE MOMENT

EDM violates both T, P symmetries

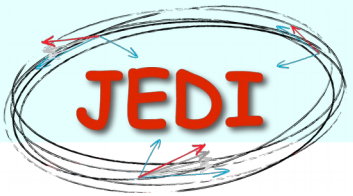


EDM violates CP symmetry
(if CPT conserved)



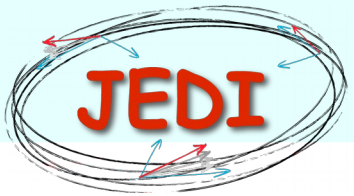
EDM is a probe for CP violation beyond the SM

CHARGED PARTICLE EDM



- No direct measurement for charged hadron EDMs
- Potentially higher sensitivity for charged hadrons (compared to neutrons):
  - longer lifetime
  - more stored polarized protons/deuterons
  - can apply larger electric fields in storage rings
- Complementary to neutron EDM
  - EDM of single particle type not sufficient to identify CPV source

EDM AT STORAGE RINGS



THOMAS - BMT EQUATION:

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

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

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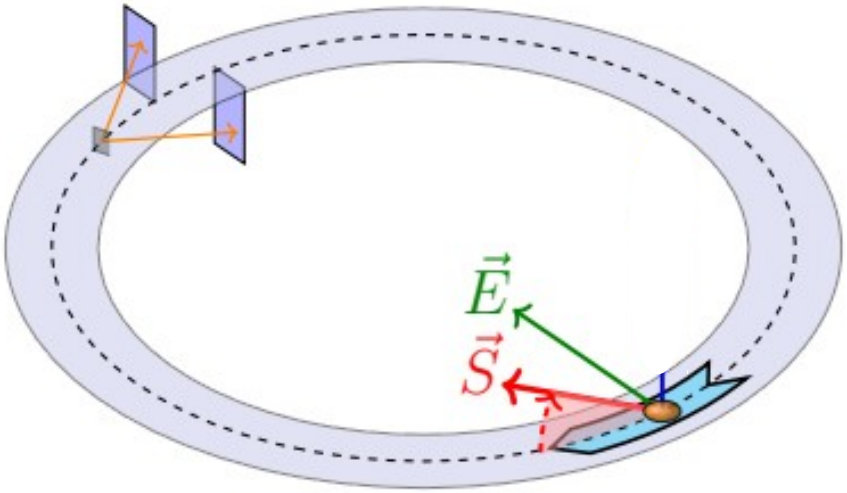
$\frac{1}{\gamma^2 - 1} \to 0$

"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 $(G - \frac{1}{\gamma^2 - 1}) = 0$

$\Rightarrow$ radial electric field causes the spin to precess out of the plane linearly



EDM FOR CHARGED PARTICLE IN 3 STAGES

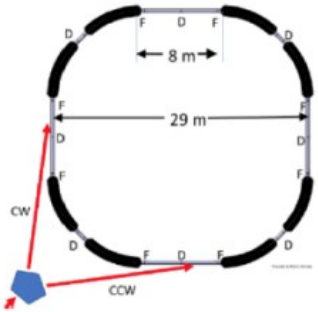
Stage 1

- precursor experiment

pure magnetic ring

Stage 2

- prototype ring



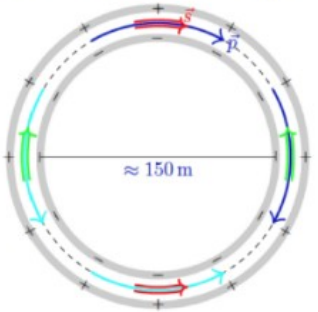
combined E/B ring

simultaneous CW-CCW beams

frozen spin

Stage 3

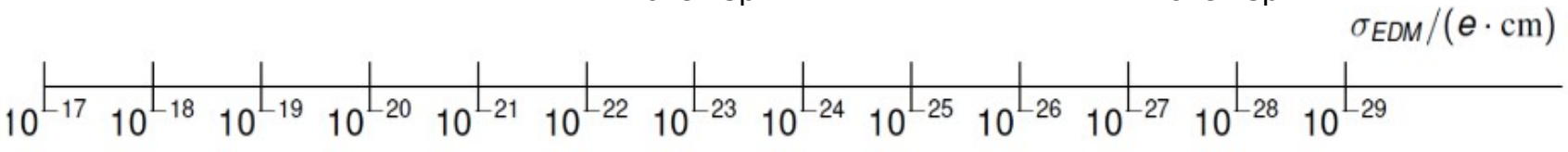
- dedicated storage ring



all electric proton ring

simultaneous CW-CCW beams

frozen spin



Talk of Joerg Pretz, 18.10.2021

* F. Abusaif et al., “Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study,” 2020.https://arxiv.org/abs/1912.07881

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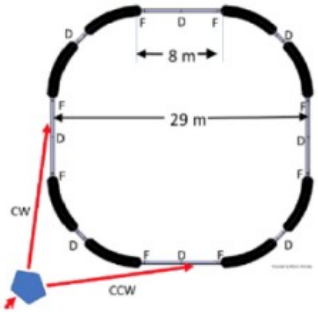

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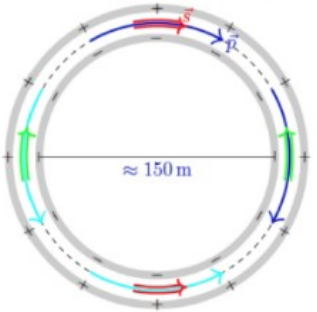

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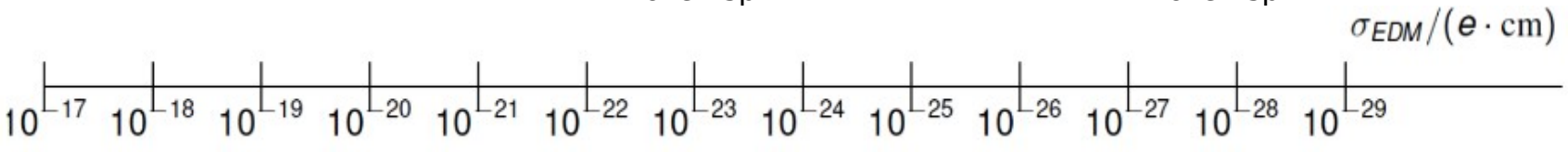

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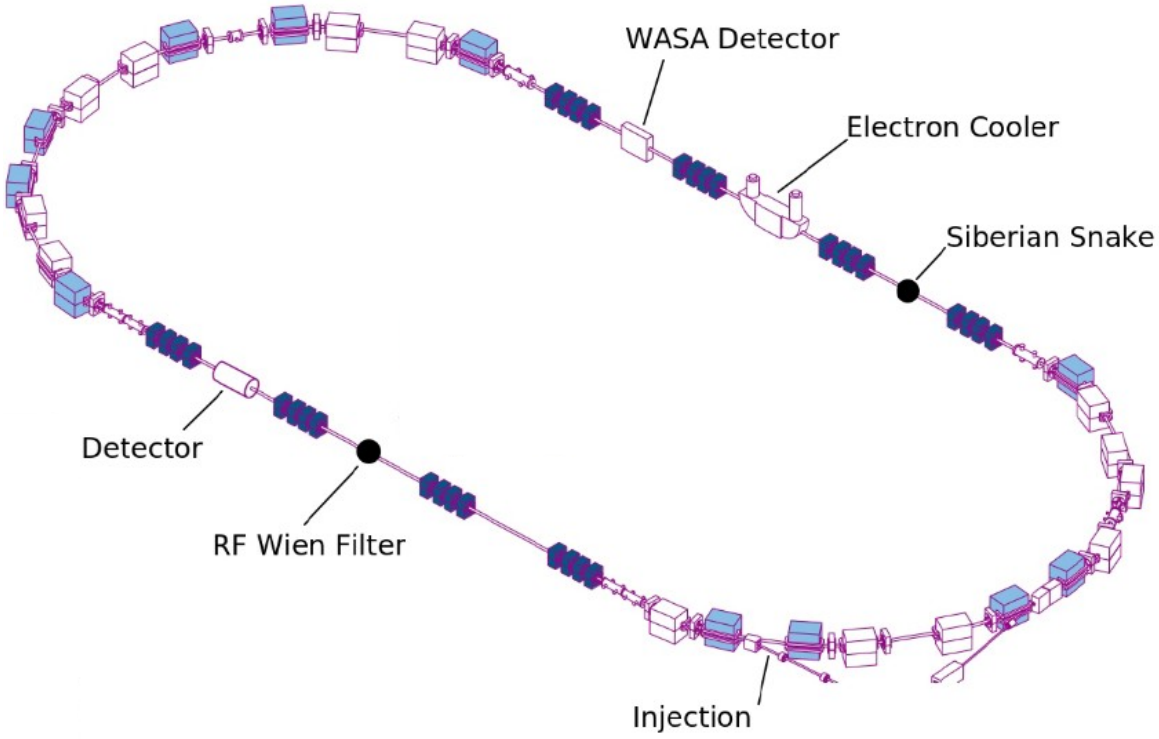
This talk: precursor experiment, with a magnetic ring COSY

PRECURSOR EXPERIMENT AT COSY

COSY (Jülich, Germany)

- 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

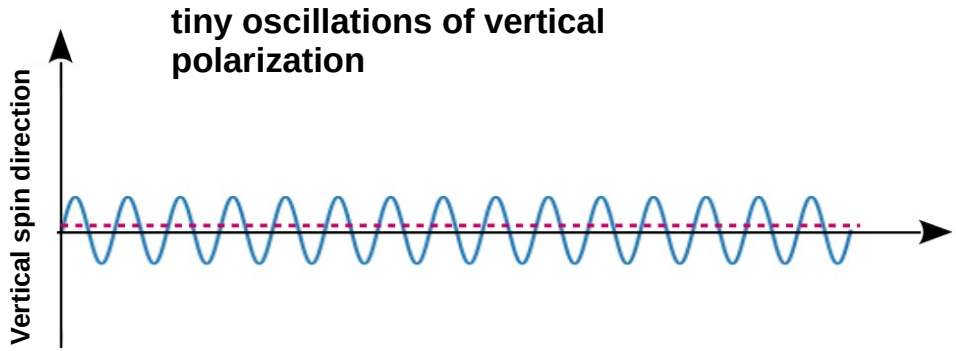
In the magnetic ring

momentum ↑↑ spin ⇨ spin kicked up

momentum ↑↓ spin ⇨ spin kicked down

⇩

no accumulation of vertical asymmetry



RF WIEN FILTER

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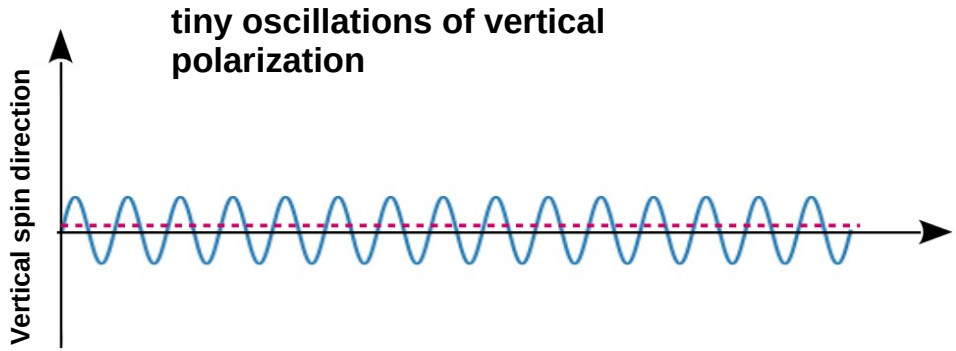
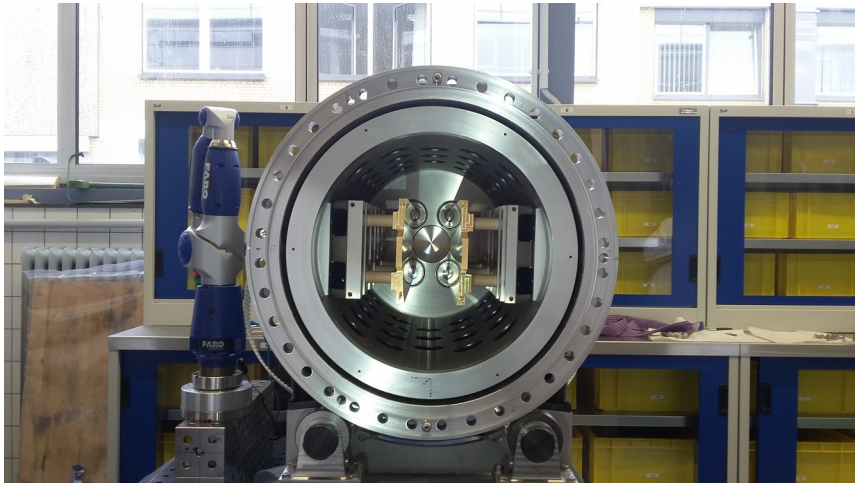


RF Wien filter

*Heberling, Hölscher and **J. Slim***

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

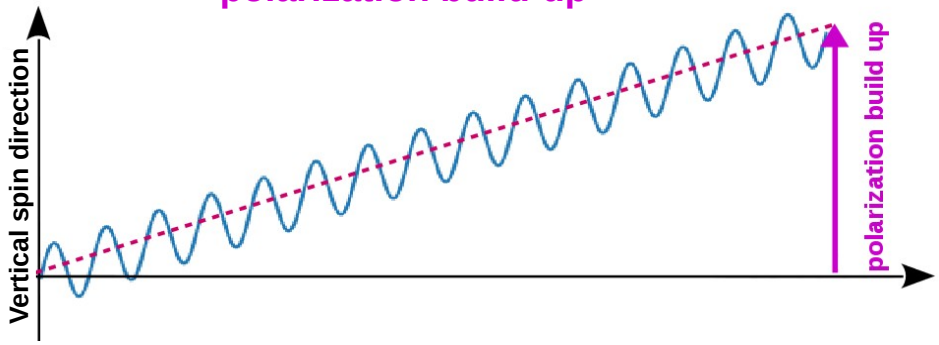
- Lorentz force $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0$
- $\vec{B} = (0, B_y, 0)$ and $\vec{E} = (E_x, 0, 0)$



phase lock between spin precession and RF Wien filter

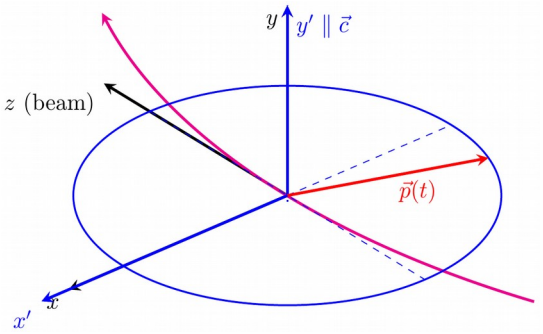
⇩

polarization build-up



EFFECT ON INVARIANT SPIN AXIS

EDM absent



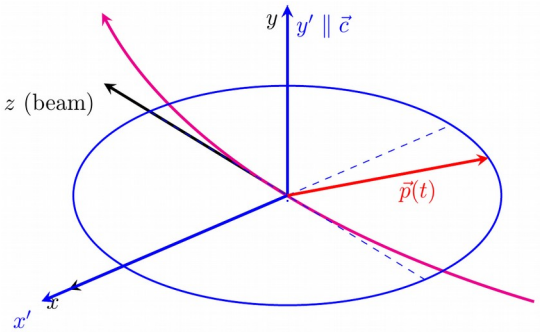
Spin vector that is invariant under one turn
spin transfer matrix is called the invariant spin axis

$$T\left(\theta+2\pi,\theta\right)=e^{-i\pi G\gamma\hat{n}_o\vec{\sigma}}$$

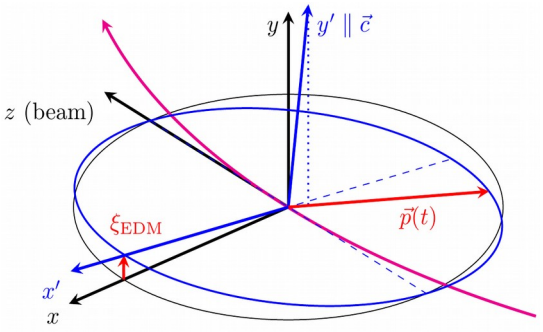
For an ideal ring (closed orbit), and w/o EDM effect,
invariant spin axis is along the direction of the guiding field

EFFECT ON INVARIANT SPIN AXIS

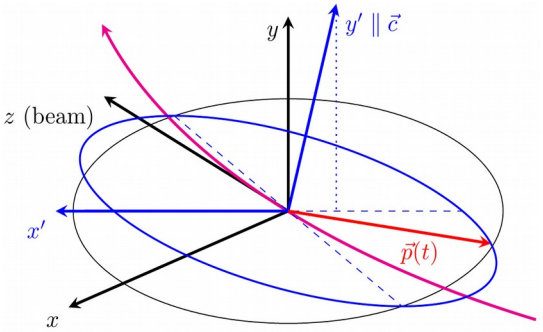
EDM absent



Pure EDM effect



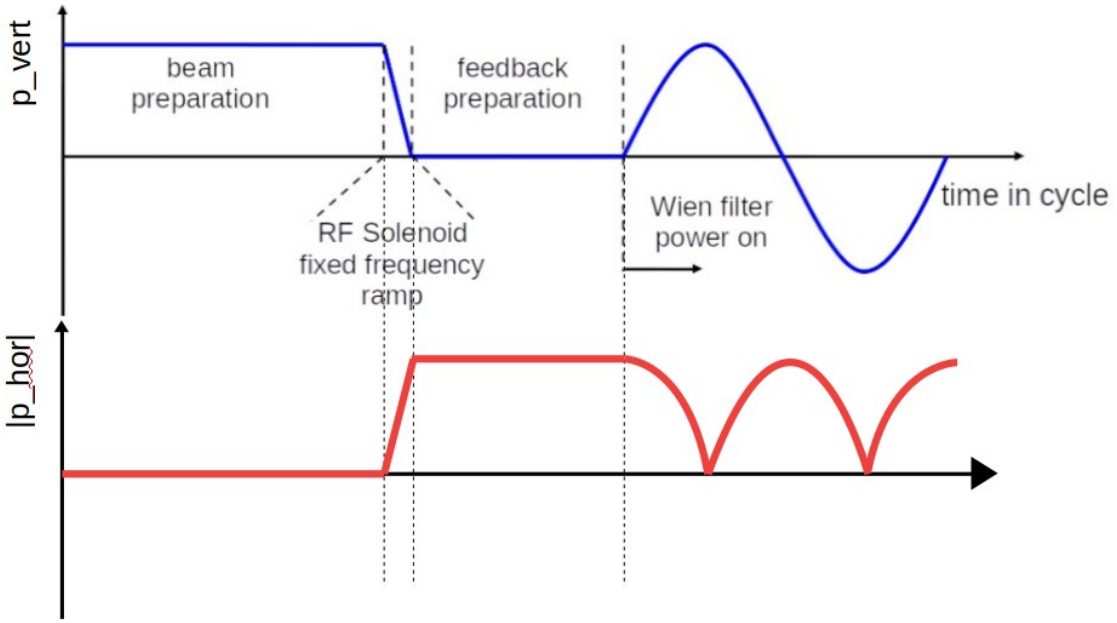
EDM + magnetic misalignments



PRINCIPLE OF MEASUREMENTS

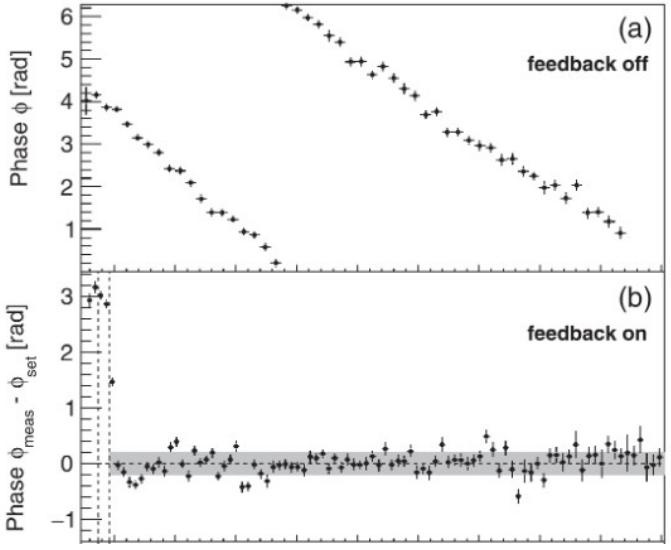
- Coherent ensembles in ring plane ➡ spin coherence time has to be longer then a measurement
- Spin precesses with 120 kHz.
- Wien filter operates on resonance
  $f = f_{COSY} + f_{spin\ pres} = 871.430$ kHz
- Phase lock between spin precession and Wien filter

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



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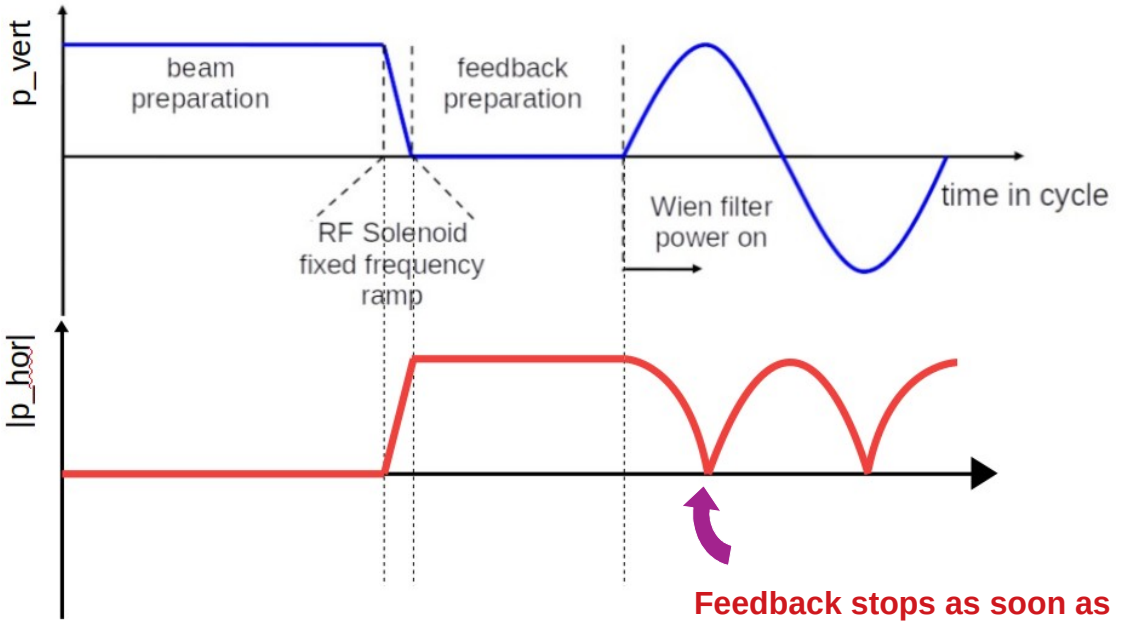


Feedback stops as soon as horizontal polarization is zero

Hempelmann, N., Phys. Rev. accel. and beams, 21(4), 042002 (2018)

PRECURSOR RUN I

Precursor experiment I November 2018:

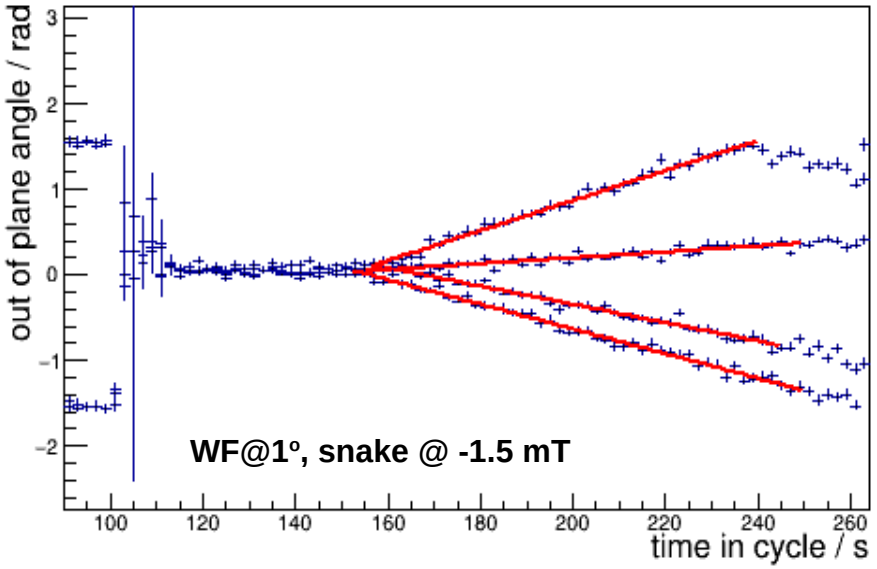
Study dependence of α(t) slope on the phase φ between WF and the spin precession

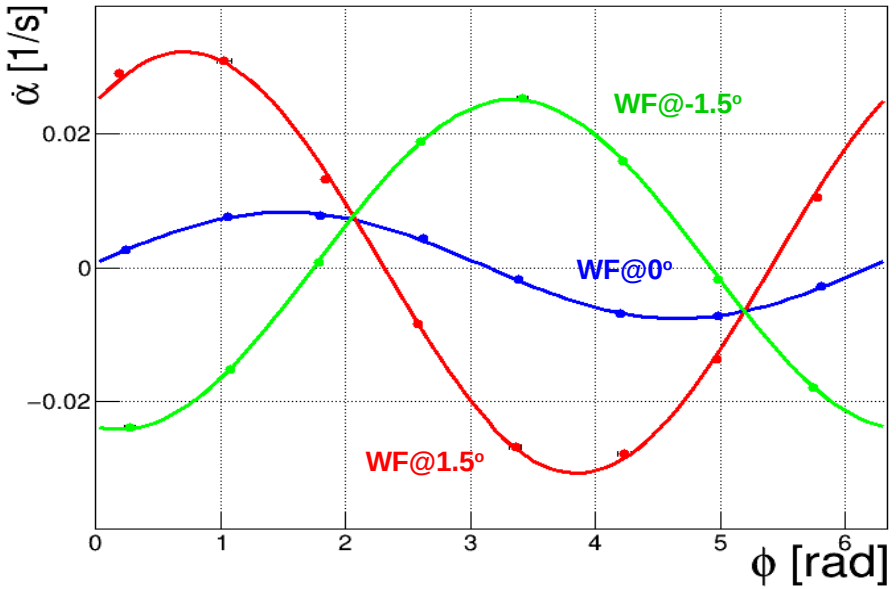
$$\alpha(t) = \arctan\left(\frac{P_y}{P_{xz}}\right)$$

Wien filter is physically rotated about the beam axis

Additional spin kick from a solenoid elsewhere in the ring

Amplitude depends on the WF rotation and the solenoid kick





PRECURSOR RUN I

Parametric resonance strength
based on initial slope

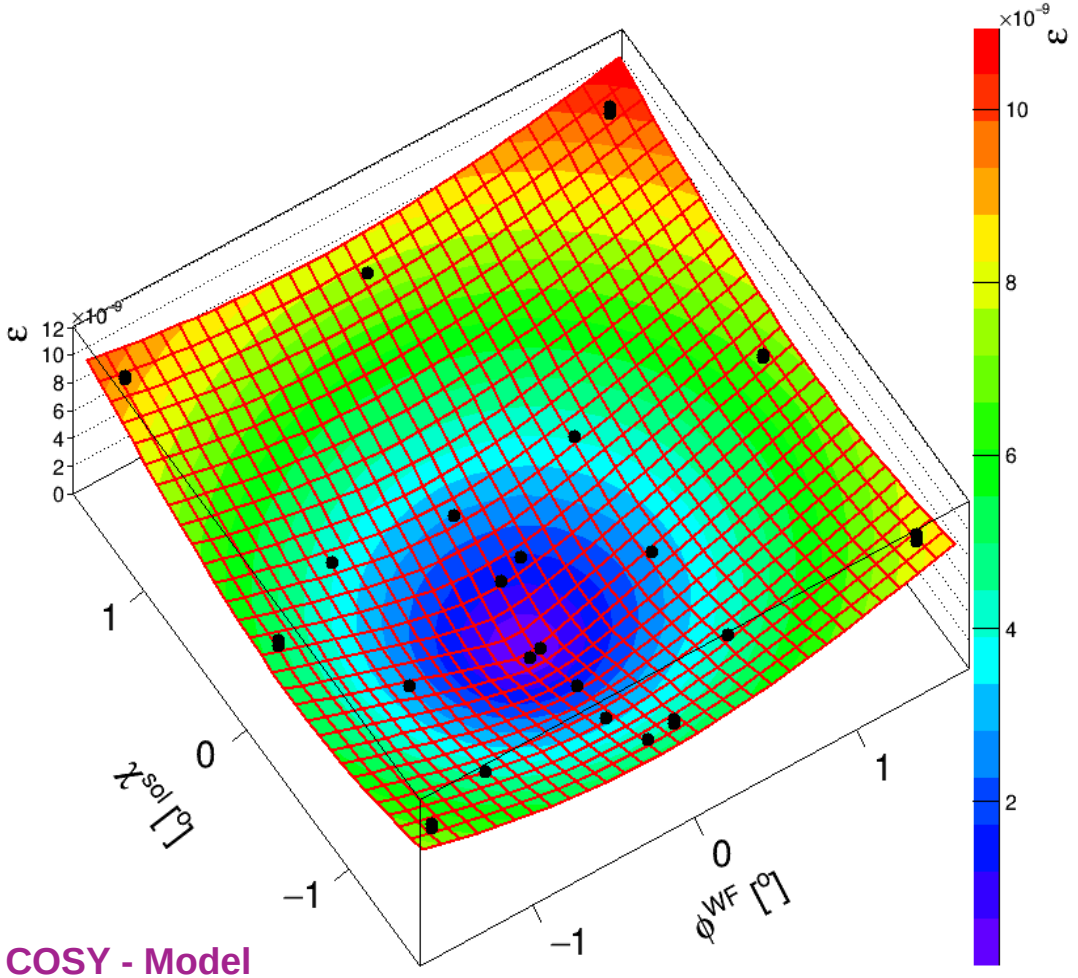
$$\varepsilon^{EDM} = \frac{\Omega^{P_Y}}{\Omega^{rev}}$$

Minimum of the surface shows orientation of precession 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



M. Vitz - Orbit Response Matrix Analysis for COSY - Model Optimization using LOCO, 18/10/2021, 21:20

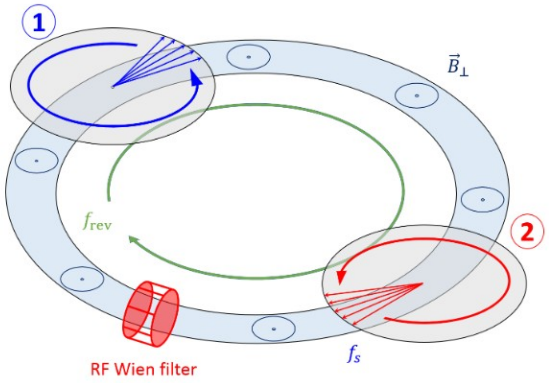
LIST OF IMPROVEMENTS

- Alignment campaigns of COSY magnet system
- Beam-based alignment
  PhD thesis T. Wagner **talk of Tim Wagner 19/10/2021, 21:20**
- 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
  PhD thesis F. Abusaif
- New JEDI polarimeter
  I. Keshelashvili and the polarimeter group **talk of Otari Javakhishvili 19/10/2021, 21:00**
- 8 high-speed RF switchers to gate the WF power for one of the bunches
  pilot bunch technique **talk of Jamal Slim 19/10/2021, 21:20**
  J. Slim, A. Nass, F. Rathmann, G. Tagliente

PRECURSOR RUN II

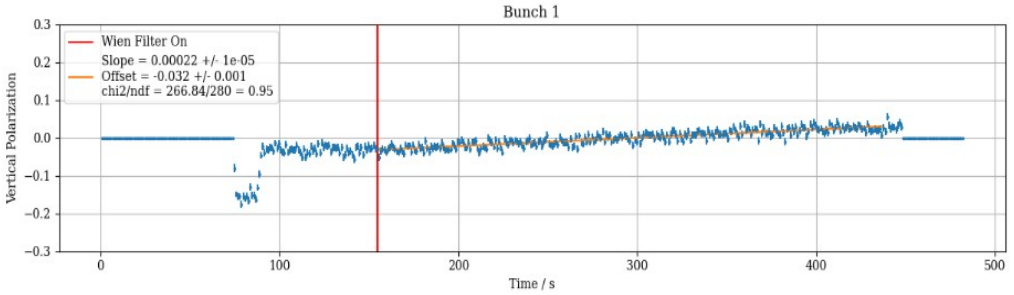
Gating of the bunch:

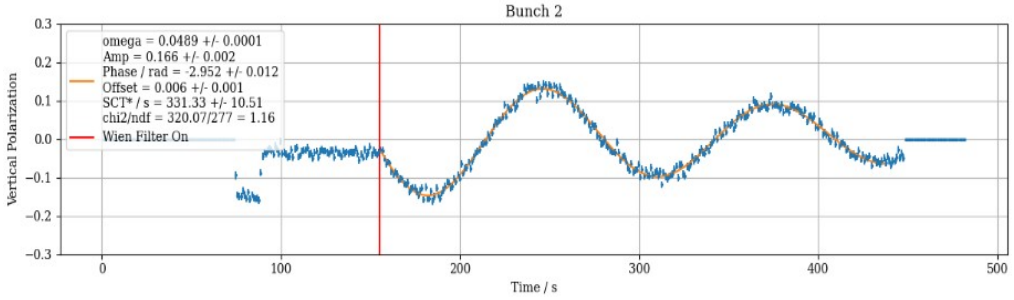
- 8 high-speed RF switches to gate the WF power for one of two bunches



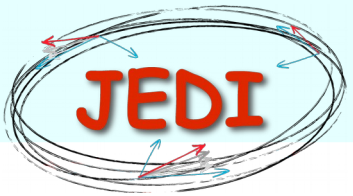
- Capable of short switch time ~ few ns

- Bunch ② feels the power and oscillate
- Bunch ① is used as pilot bunch for phase locking





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. Analysis of data ongoing.
- 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
- COSY remains a unique facility for such studies.