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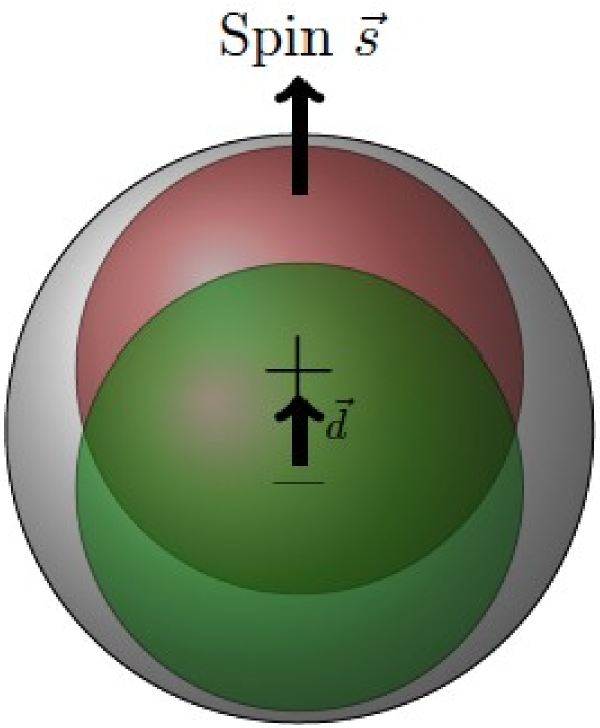
Progress towards the first direct measurement of deuteron EDM at COSY-Jülich storage ring

September 2, 2019 | Sergey Dymov JINR (Dubna), Ferrara Universisy

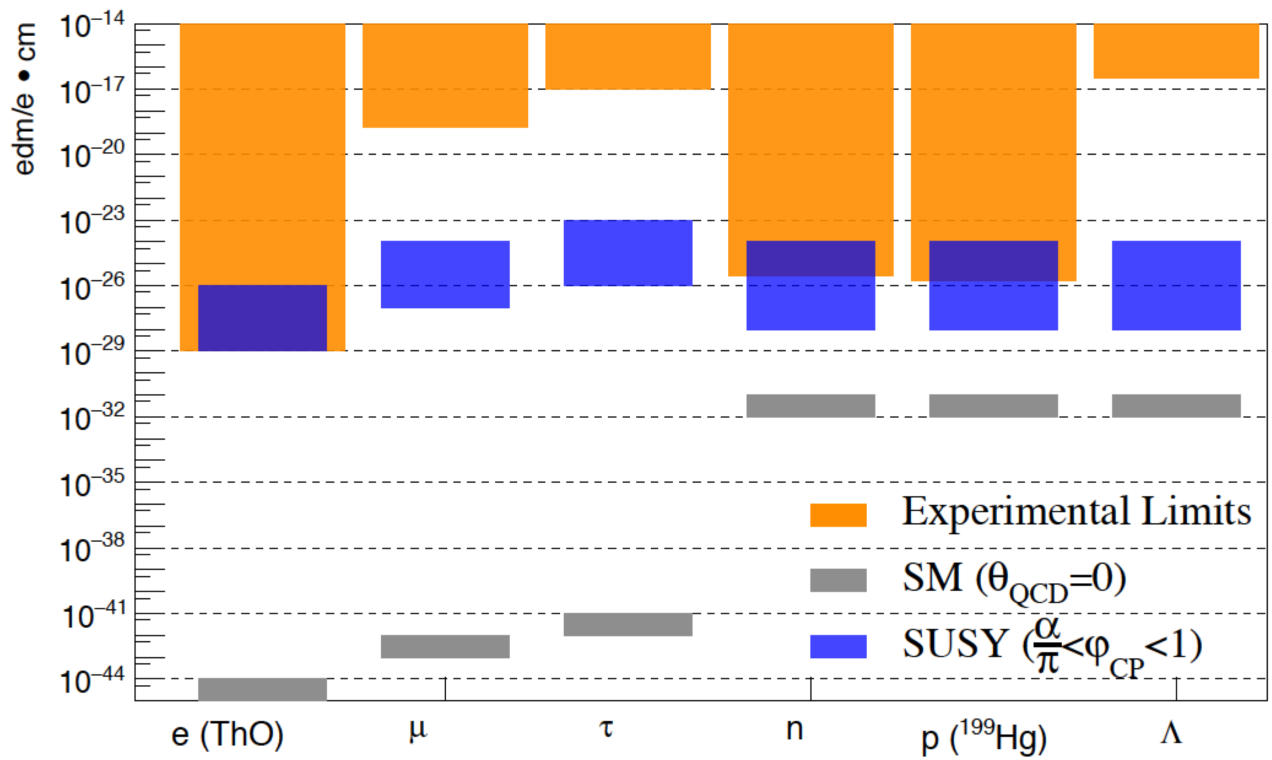
Electric dipole moments (EDM)



- Permanent separation of + and – charge
- Fundamental property of particles (like magnetic moment, mass, charge)
- Possible only via violation of time-reversal *T* *(CP)* and parity *P*
- *Nothing to do with EDMs of molecules (e.g. H_2O)*
- *connection to matter-antimatter asymmetry*

Standard Model	
Weak interaction	
CKM matrix	→ unobservably small EDMs
Strong interaction	
θ_{QCD}	→ best limit from neutron EDM
beyond Standard Model	
e.g. SUSY	→ accessible by EDM measurements

EDM: Current upper limits



Storage rings (FZ Jülich): EDMs of charged hadrons: *p, d, ^{3}He*

Why Charged Particle EDMs?

- No direct measurement for charged hadron EDMs
- Potentially higher sensitivity (compared to neutrons):
  - *longer lifetime;*
  - *more stored protons/deuterons*
  - *can apply larger electric fields in storage rings*
- complementary to neutron EDM:

  EDM of single particle not sufficient to identify CP-V source

General case

The spin motion for relativistic particles in a storage ring is determined by the **Thomas-BMT equation**

MDM EDM

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m}\left\{ G_\gamma \vec{B} + \left(\frac{1}{\gamma^2-1} - G\right)\frac{\vec{\beta}\times\vec{E}}{c} + d\,\frac{m}{q\hbar S}\left(\vec{E} + c\vec{\beta}\times\vec{B}\right)\right\} \times \vec{S}$$

Ω : angular precession frequency

G : anomalous magnetic moment

d : electric dipole moment

γ : Lorentz factor

Ideal case

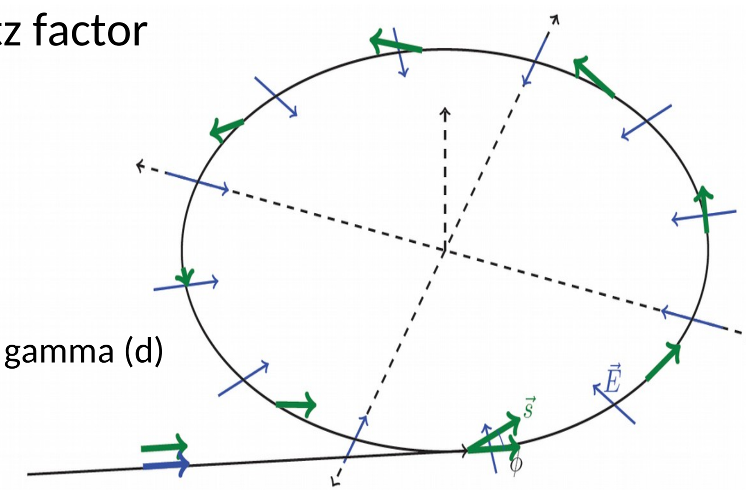
Inject particles with spin pointing towards momentum direction

„Frozen Spin": without EDM spin stays aligned to momentum:

achievable for B=0, G>0 (p) **or** special combination of E, B and gamma (d)

EDM couples to electric bending fields

Slow buildup of EDM related vertical polarization



Options for storage ring experiment

time

	☺	☹
1.) pure magnetic ring	existing (upgraded) COSY ring can be used, shorter time scale	lower sensitivity, precession due to G, i.e. no **frozen spin**
2.) combined ring	works for p, d, ^{3}He, smaller ring radius	both $\vec{E}$ and $\vec{B}$ B field reversal for $\circlearrowleft$, $\circlearrowright$ required
3.) pure electric ring	no $\vec{B}$ field needed, $\circlearrowleft$, $\circlearrowright$ beams simultaneously	works only for particles with $G > 0$ (e.g. p)

Document submitted to ESPP in Dec. 2018 (arXiv:1812.08535, CERN yellow report CERN-PBC-REPORT-2019-002 in preparation)

This talk: experiment with a magnetic ring (COSY), a “precursor” measurement

Achievements at COSY

- High precision spin tune measurements (10^{-10} in 100 sec)
- Long polarization lifetime (~1000 sec) with 6-pole magnets
- Feedback for the WF and the spin phase lock-up
- Waveguide RF Wien filter
- Invariant spin axis measurement
- Measurement of *pC*- and *dC*- analysing powers
- Orbit control
- Beam based alignment
- Beam position monitor with Rogowski coils
- Electrostatic and combined deflector development

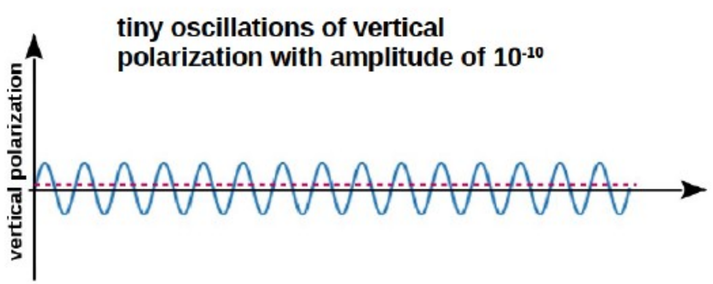
Precursor measurement with RF Wien filter

In all-magnetic ring (COSY) radial E-field in the particle rest frame is a relativistic effect

Problem: vertical B-field makes spin precess in horizontal plane

Magnetic ring

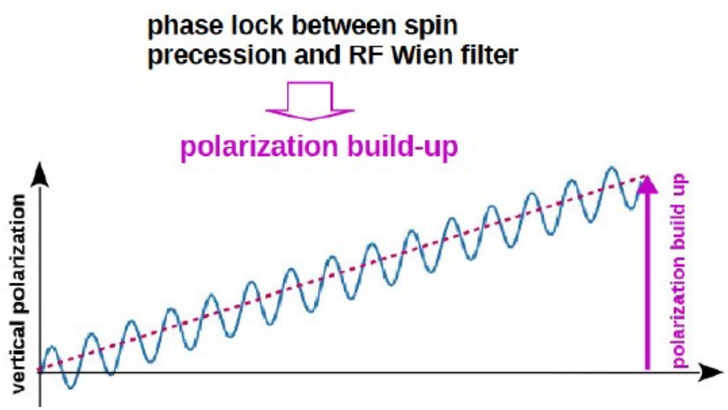
- Momentum $\uparrow\uparrow$ spin $\Rightarrow$ spin kicked up
- Momentum $\uparrow\downarrow$ spin $\Rightarrow$ spin kicked down
- $\Rightarrow$ no accumulation of vert. asymmetry



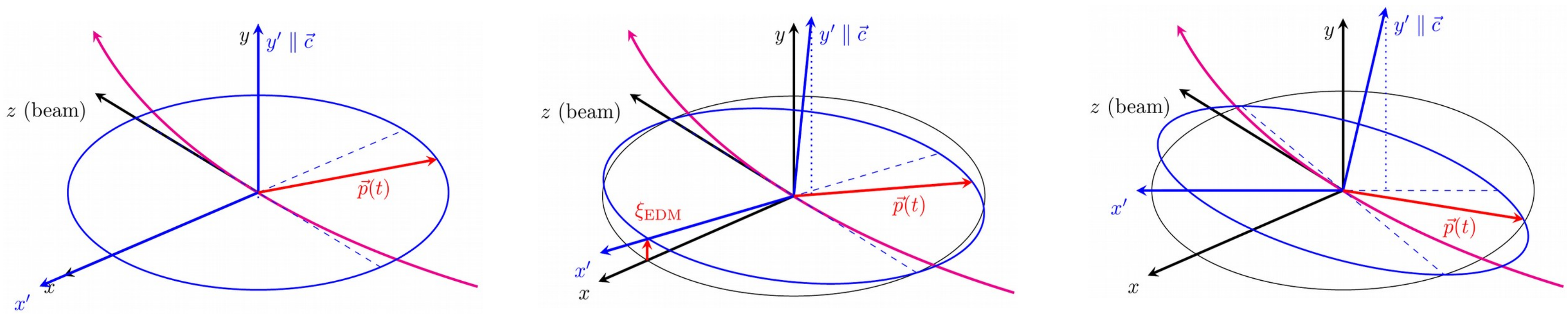
Solution:

RF-Wien filter

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



Effect of EDM on stable spin axis



No EDM

EDM effect

Magnetic misalignment

<u>EDM tilts the stable spin axis</u>

- Presence of EDM $\rightarrow \varepsilon_{EDM} > 0$
  - $\rightarrow$ spin precess around the $\vec{c}$ axis
  - $\rightarrow$ oscill. vert. polarization $p_y(t)$

Polarization build-up

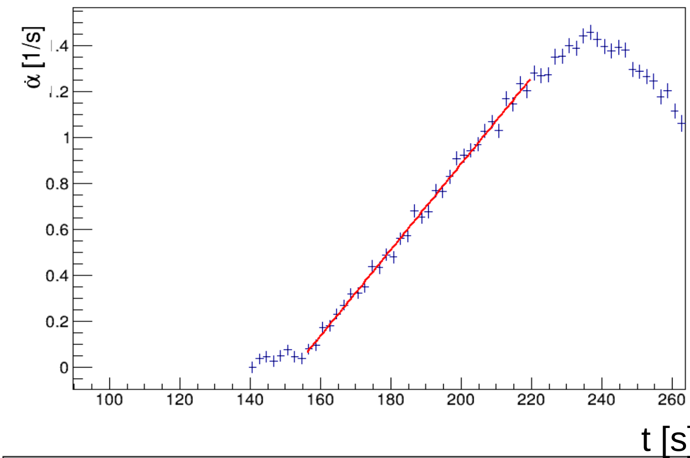
- Wien filter operated with B filed normal to the ring plane

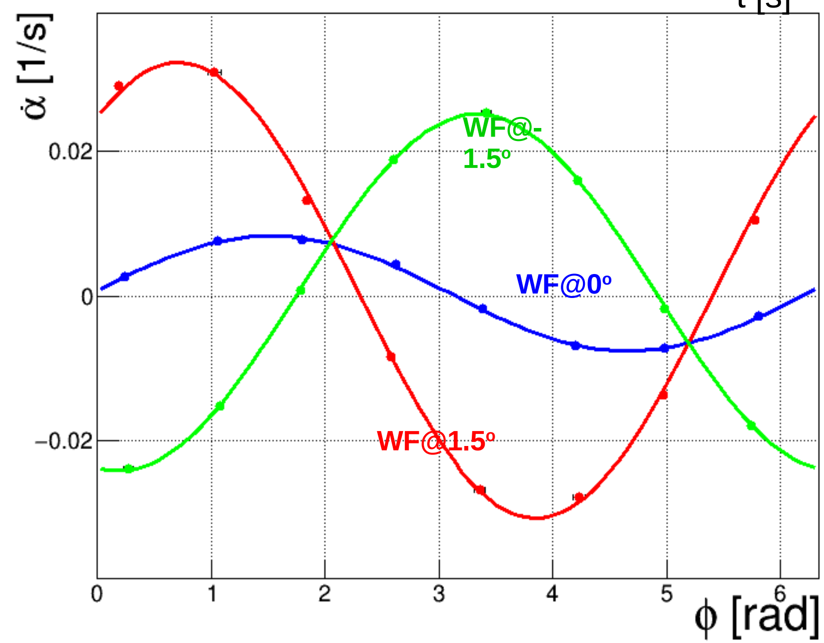
$$\alpha(t)=\arctan\left(\frac{P_y}{P_{xz}}\right)$$

- Wien filter is physically rotated about the beam axis + additional spin kick from a solenoid elsewhere in the ring

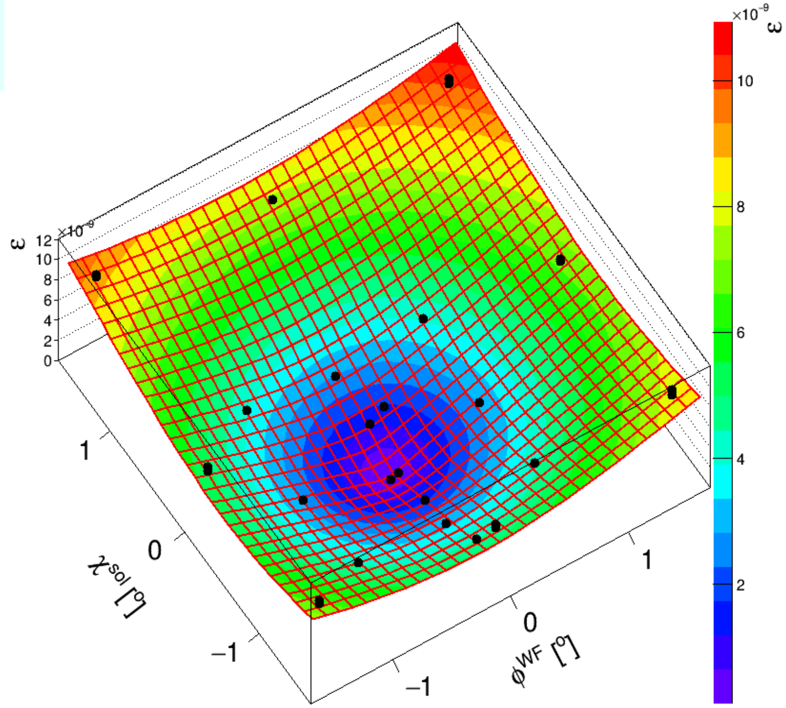
- Study dependence of Py initial slope on the phase phi between WF and the spin precession

- Amplitude depends on the WF rotation and the kick





FIRST RESULTS



Orientation of precession axis at location of RF Wien filter including EDM determined from the minimum of the surface

Observed effect limits $d_{EDM} < 10^{-17}$

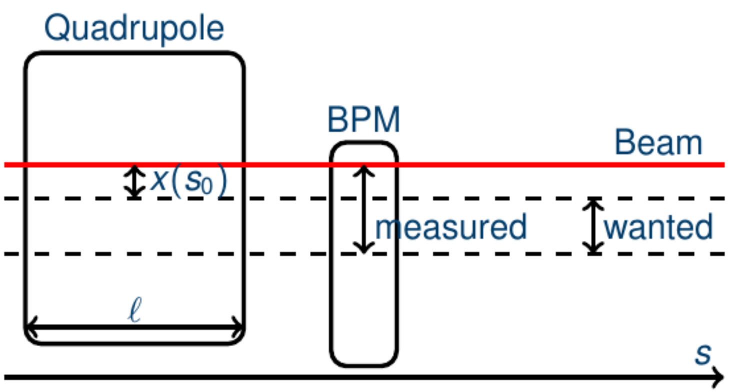
Spin tracking calculations shall provide the orientation of precession axis without EDM

Second run with improved setup (new feedback, new polarimeter, better beam positioning, improved ExB match in WF etc) is planned for 2020

Beam based alignment

Goal: pass the beam through the center of quadrupoles better then 100 mum

Need a good knowledge of BPM to quadrupole offset

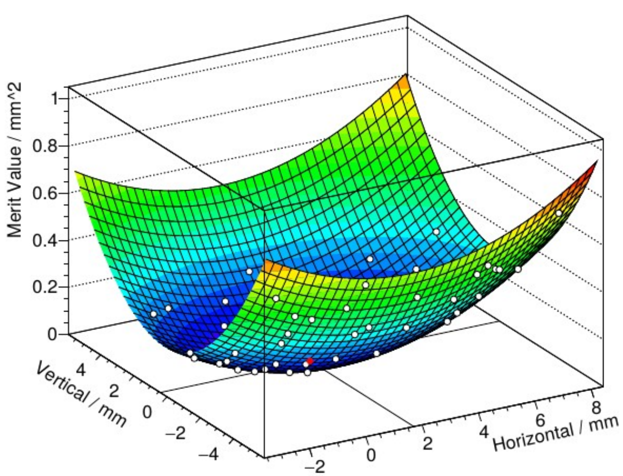


Offset Δx as a function of beam position in quad x, quad strength k and (not perfectly known) setup parameters

$$\Delta x(s) = \frac{\Delta k \cdot x(s_0) l}{B\rho} \cdot \frac{1}{1 - k\frac{l\beta(s_0)}{2B\rho \tan \pi\nu}} \cdot \frac{\sqrt{\beta(s)}\sqrt{\beta(s_0)}}{2 \sin \pi\nu} \cos[\phi(s) - \phi(s_0) - \pi\nu]$$

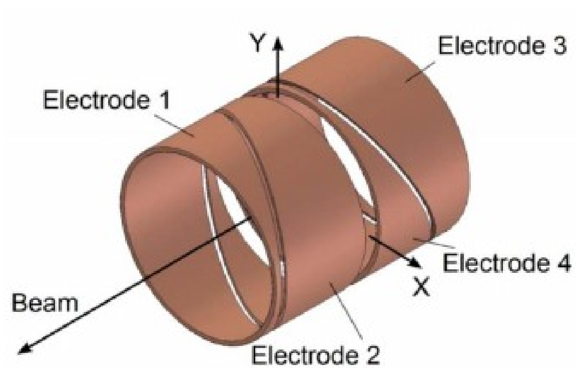
Vary x and k, minimize FOM

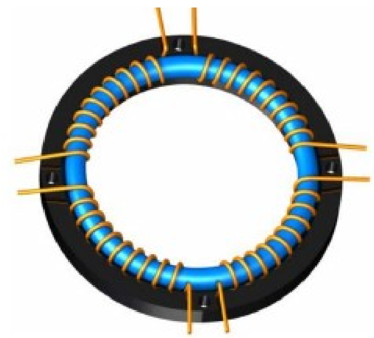
$$f = \frac{1}{N_{BPM}} \sum_{i=1}^{N_{BPM}} (x_i(+\Delta k) - x_i(-\Delta k))^2 \propto (x(s_0))^2$$



Compact BPM based on Rogowski coil

Main advantage: short installation length (~1cm in beam direction)





Conventional BPM

- Easy to manufacture
- Length ~ 20 cm
- Resolution ~ 10 μm

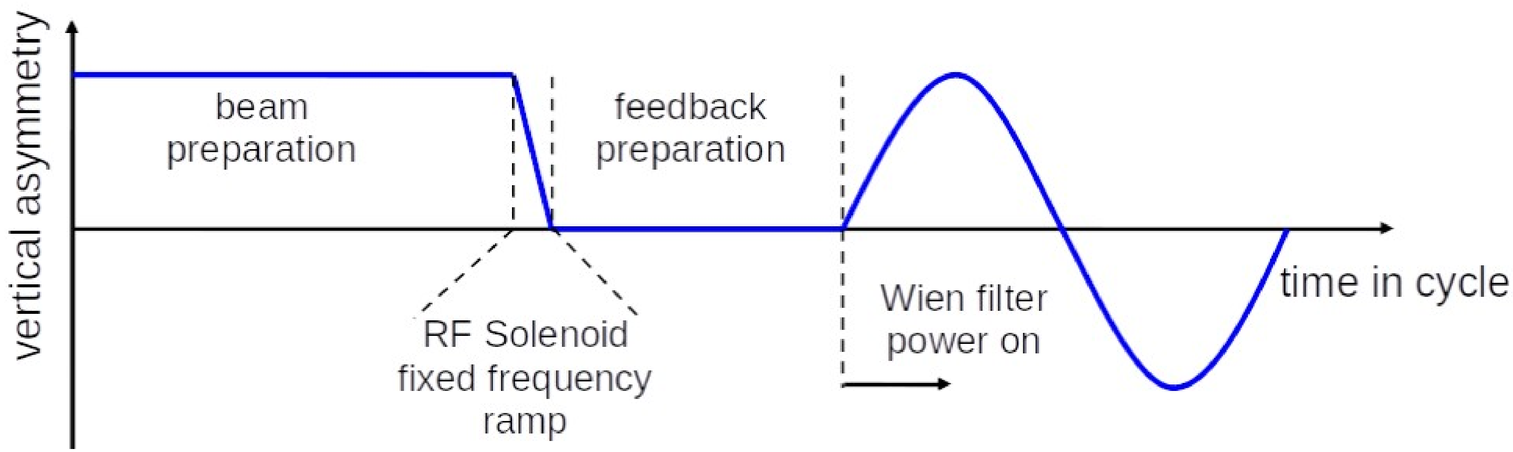
Rogowski coil (warm)

- Excellent RF-signal response
- Length ~ 1 cm
- Resolution ~ 1.25 μm

2 coils installed at entrance and exit of RF Wien filter

Pilot bunch-based spin phase-lock feedback (1)

Current feedback: the basic workflow

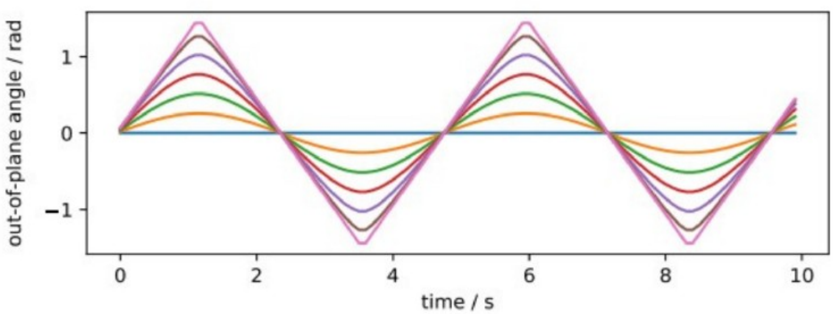


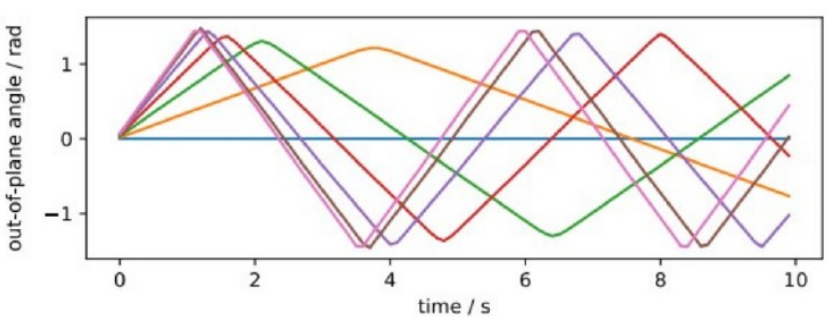
Feedback analyses horizontal spin precession and defines the spin frequency (tune)

1. adjust WF frequency to spin precession freq. before WF power on
2. Feedback monitors tune and adjust WF frequency to maintain the relative phase

Pilot bunch-based spin phase-lock feedback (2)

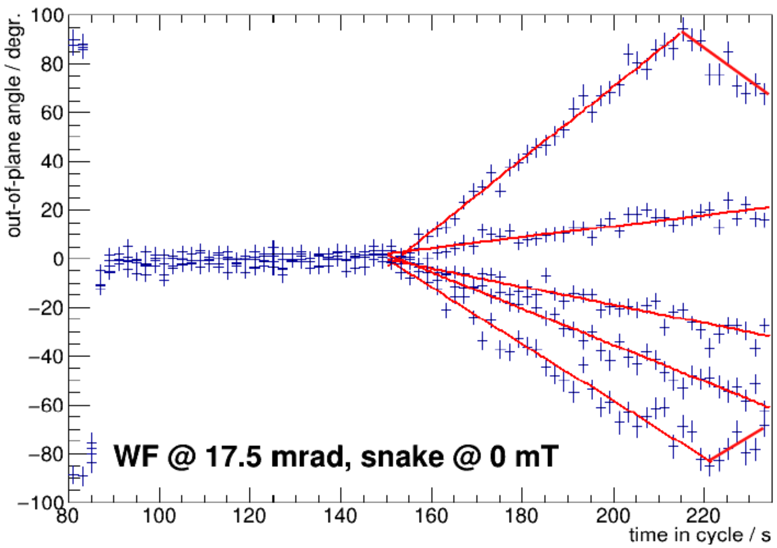
Current feedback: simulation of the phase-lock system





With feedback being turned on, the slopes of the slow P_y oscillations are preserved but not the frequency

Problem: feedback fails for too low horizontal polarization (too high P_y)

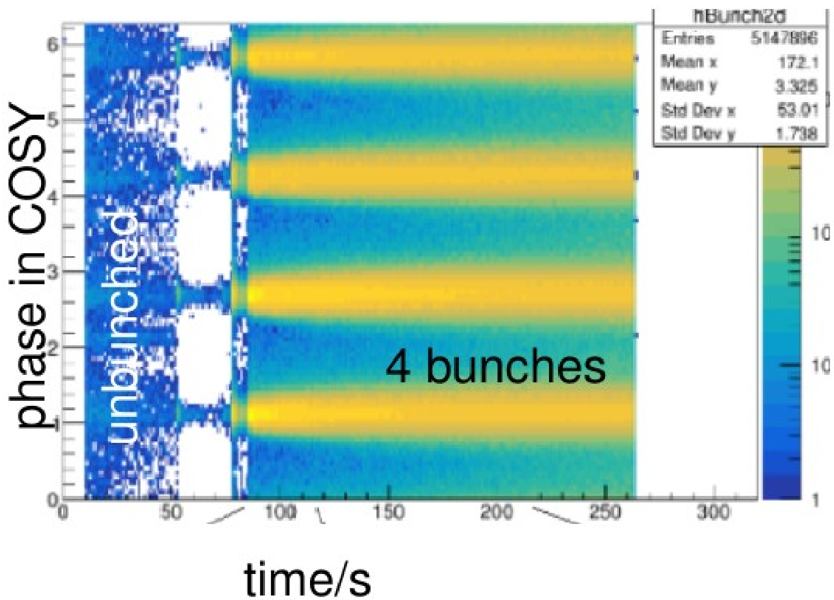


A measurement example of the vertical polarization build-up with the phase-lock feedback turned on

Pilot bunch-based spin phase-lock feedback (3)

Solution: multi-bunch beam structure (4 bunches beam has been tested)

- the fields of the RF Wien filter will be visible to only three of four bunches
- leads to a RF field-free bunch, also known as pilot bunch
- the spin tune will be only measured using the pilot bunch
- the feedback system continuously maintains the spin precession frequency
- the bunches other than pilot can have arbitrarily chosen spin phases



First test in April 2019

Thank you!