SEARCHES FOR ELECTRIC DIPOLE MOMENTS (EDM) AT A STORAGE RING WITH JEDI

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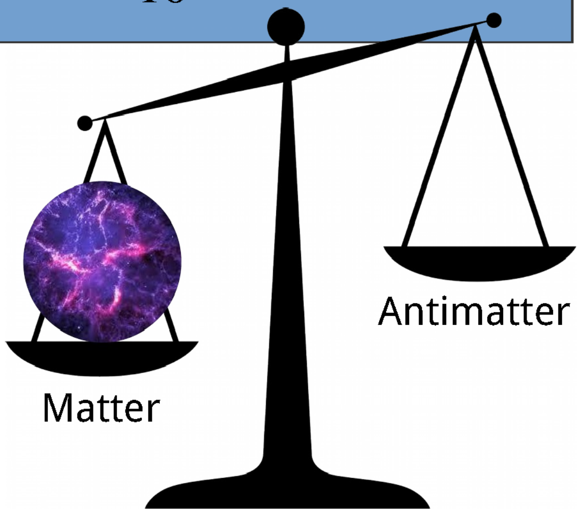
MOTIVATION

Baryon Asymmetry Problem

Baryon Asymmetry	Observation	Standard Cosmological Model
$(N_B - N_{\bar{B}}) / N_\gamma$	6×10^{-10}	$\sim 10^{-18}$



Preconditions needed to explain it (Sakharov):

- **$\mathcal{C}$ and $\mathcal{CP}$ violation**
- Baryon number violation
- Thermal non-equilibrium in the early Universe

$\mathcal{CP}$ violation in Standard Model

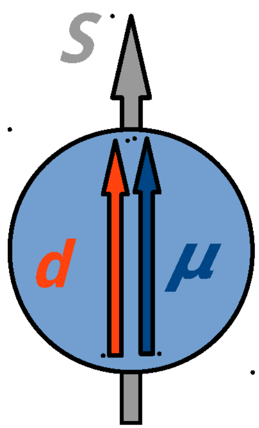
- **Electroweak sector** (CKM matrix well established)
- **Strong interactions** (θ-term, strong-$\mathcal{CP}$ puzzle)

Predictions orders of magnitude **too small** to explain the asymmetry!

New sources of $\mathcal{CP}$ violation can be seen in EDM of particles

ELECTRIC DIPOLE MOMENT

$\mathcal{CP}$-symmetry violation

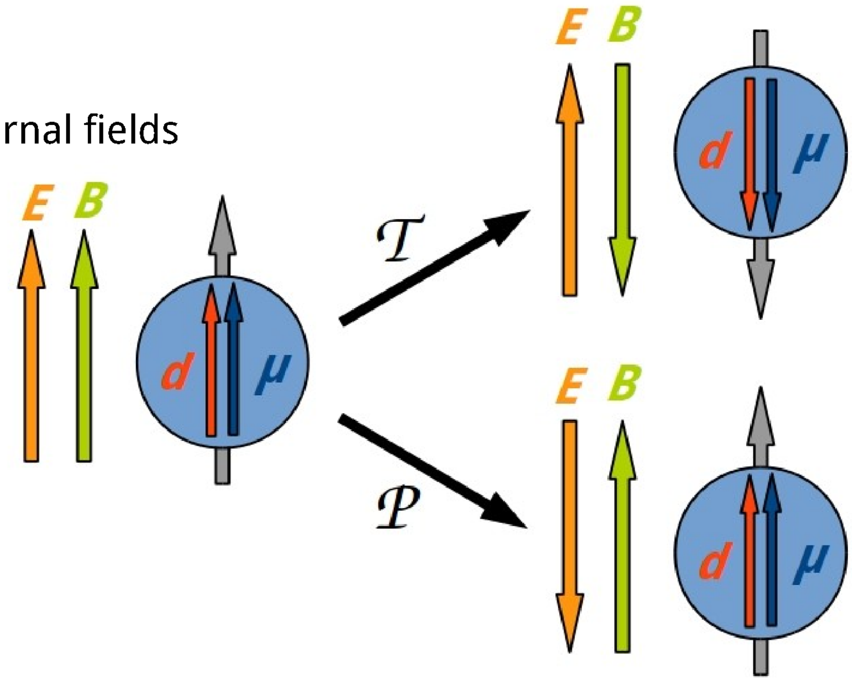


$$\vec{d} = \eta \cdot \frac{q}{2mc}\vec{S}$$

$$\vec{\mu} = g \cdot \frac{q}{2m}\vec{S}$$

Pseudo vectors

External fields



The observable quantity - Energy:

- of electric dipole in electric field
- of magnetic dipole in magnetic field

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

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

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

H violates $\mathcal{T}$ and $\mathcal{P}$-symmetry if ***d≠0***

⇩

$\mathcal{T}$ violation

⇩

$\mathcal{CP}$ violation ($\mathcal{CPT}$ conserved)

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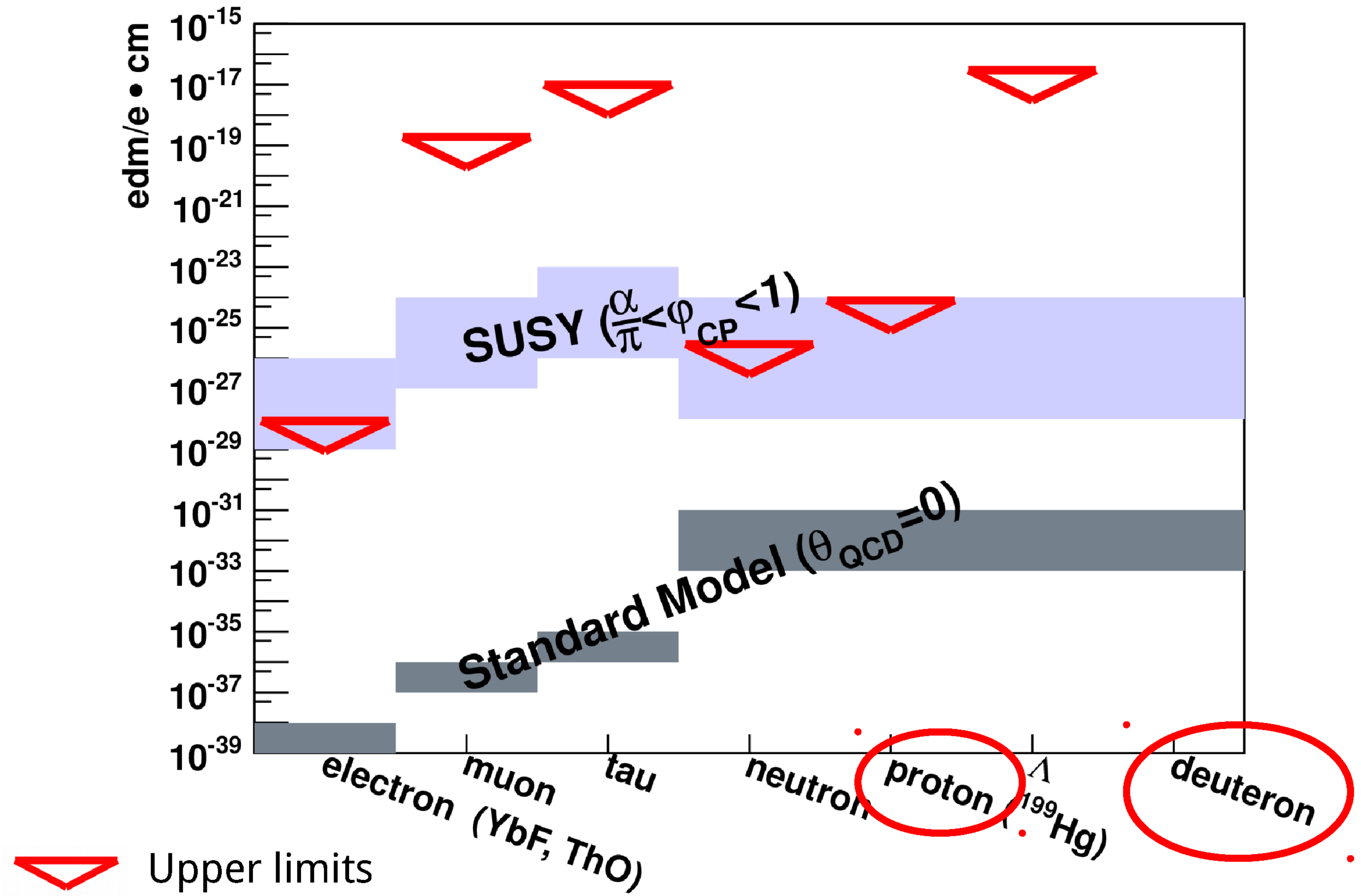
ELECTRIC DIPOLE MOMENT

Current limits



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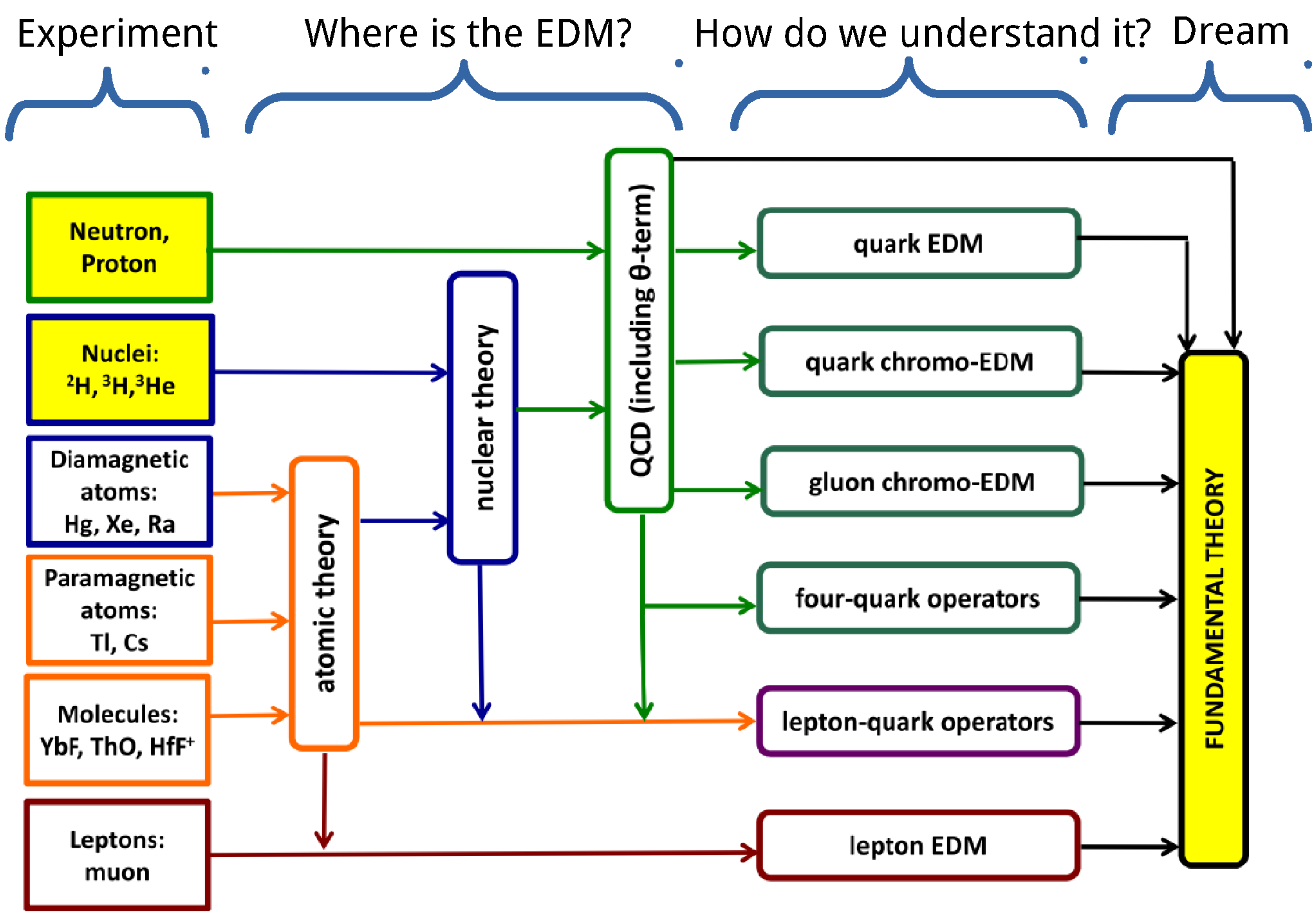
MOTIVATION

Disentanglement the fundamental source(s) of EDMs



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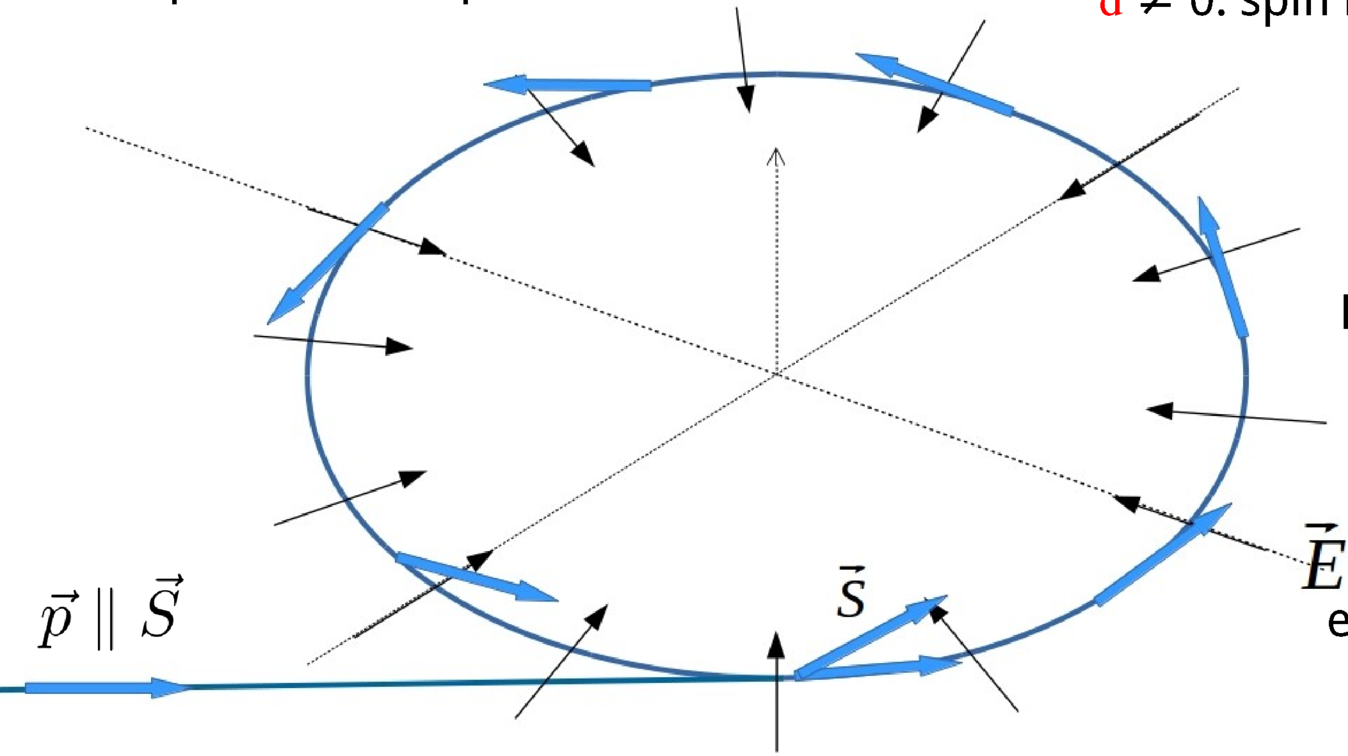
PRINCIPLE OF EDM MEASUREMENT

Charged Particles in a Storage Ring

General idea: Observation of **EDM** interaction with **electric field**

Simplified case – pure E field:



d ≠ 0: spin rotation out of horizontal plane

$$\frac{d\vec{S}}{dt} \sim d\vec{E} \times \vec{S}$$

Build-up of **vertical polarization**

d ∝ spin rotation angle

EDM ~ 10^{-29} e·cm

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effect of the order of μdeg/hour

Extremely small effects!

“Frozen spin” - Spin parallel to momentum

EXPERIMENTAL REQUIREMENTS

High precision storage ring	alignment, stability, field homogeneity
Polarized hadron beams	P = 0.8
High intensity beams	$N = 4 \times 10^{10}$ per fill
Large electric fields	E = 10 MV/m
Long spin coherence time	$\tau = 1000$ s
Polarimetry	analyzing power A = 0.6, acc. f = 0.005

$$\sigma_{\text{stat}} \approx \frac{1}{\sqrt{Nf}\tau PAE} \Rightarrow \sigma_{\text{stat}}(1\text{ year}) \approx 10^{-29} e\text{cm}$$

Challenge: systematic uncertainties on the same level!

Even in Pure Electric Ring – lots of sources of systematic uncertainties
Very small radial B field can mimic an EDM effect: $\mu B_r \sim dE_r$

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STORAGE RING EDM MEASUREMENTS

- Only EDM storage ring measurement: muon (parasitic measurement to g-2)

- **Cooler Synchrotron COSY** at Forschungszentrum Jülich, Germany
  - ✓ magnetic storage ring
  - ✓ polarized proton and deuteron beams up to 3 GeV/*c*

⇩

Ideal **starting point** for proof of principle experiment

EDMs of charged hadrons: p, **d**

R&D with deuterons
p = 1 GeV/c
G = -0.14256177(72)
$f_s \approx$ 120 kHz
$f_{rev} \approx$ 750 kHz

$$\nu_s = \frac{\text{spin revolutions}}{\text{turn}} \approx G\gamma \approx -0.16$$

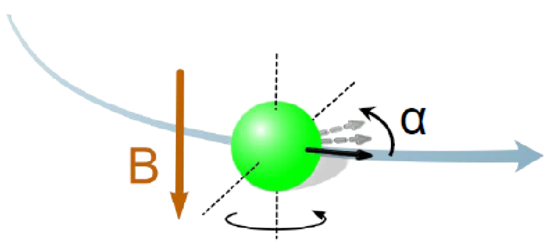
SPIN IN PURELY MAGNETIC RING

Thomas-BMT equation:

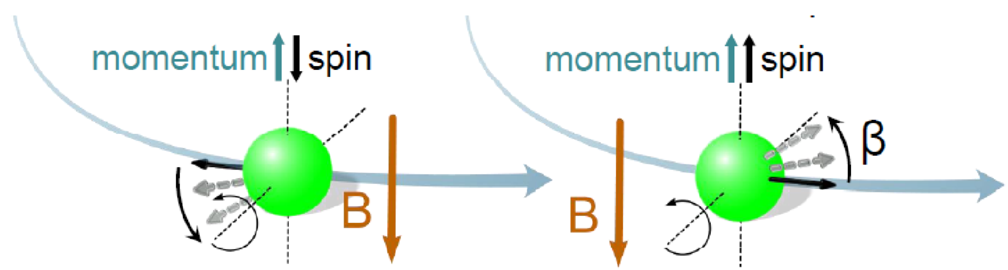
In storage rings (magnetic field – vertical, electric field - radial)

Magnetic dipole moment Electric dipole moment

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0}\left\{G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G\right)\frac{\vec{\beta} \times \vec{E}}{c} + d\,\frac{m_0}{q\hbar S}\left(\vec{E} + c\vec{\beta} \times \vec{B}\right)\right\} \times \vec{S}$$



Magnetic dipole moment



Electric dipole moment

MDM causes fast spin precession in horizontal plane
EDM causes small vertical polarization buildup oscillating up and down

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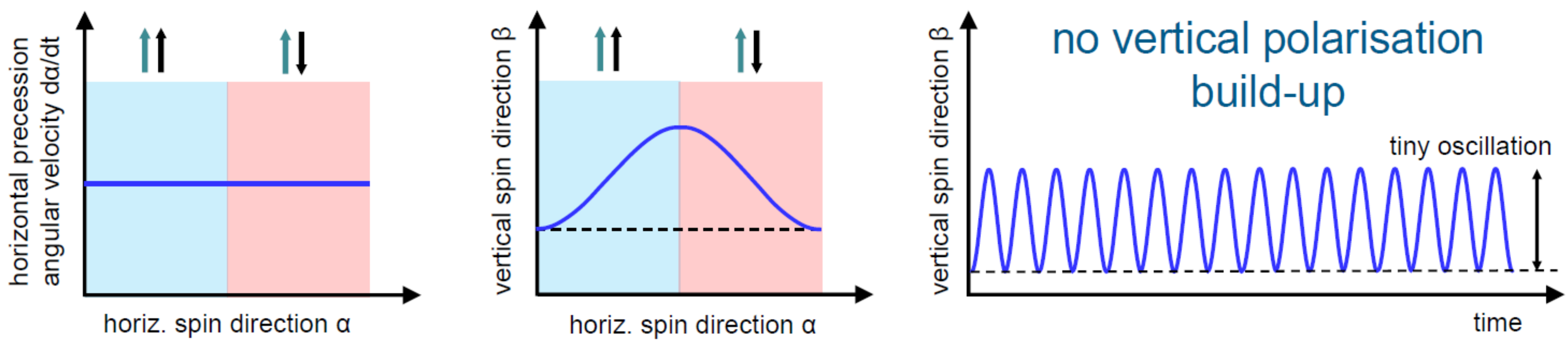
SPIN IN PURELY MAGNETIC RING

50% of time

momentum ↑↑ spin — Spin tilted up

50% of time

momentum ↑↓ spin — Spin tilted down



SPIN IN PURELY MAGNETIC RING

50% of time

momentum ↑↑ spin   Spin tilted up

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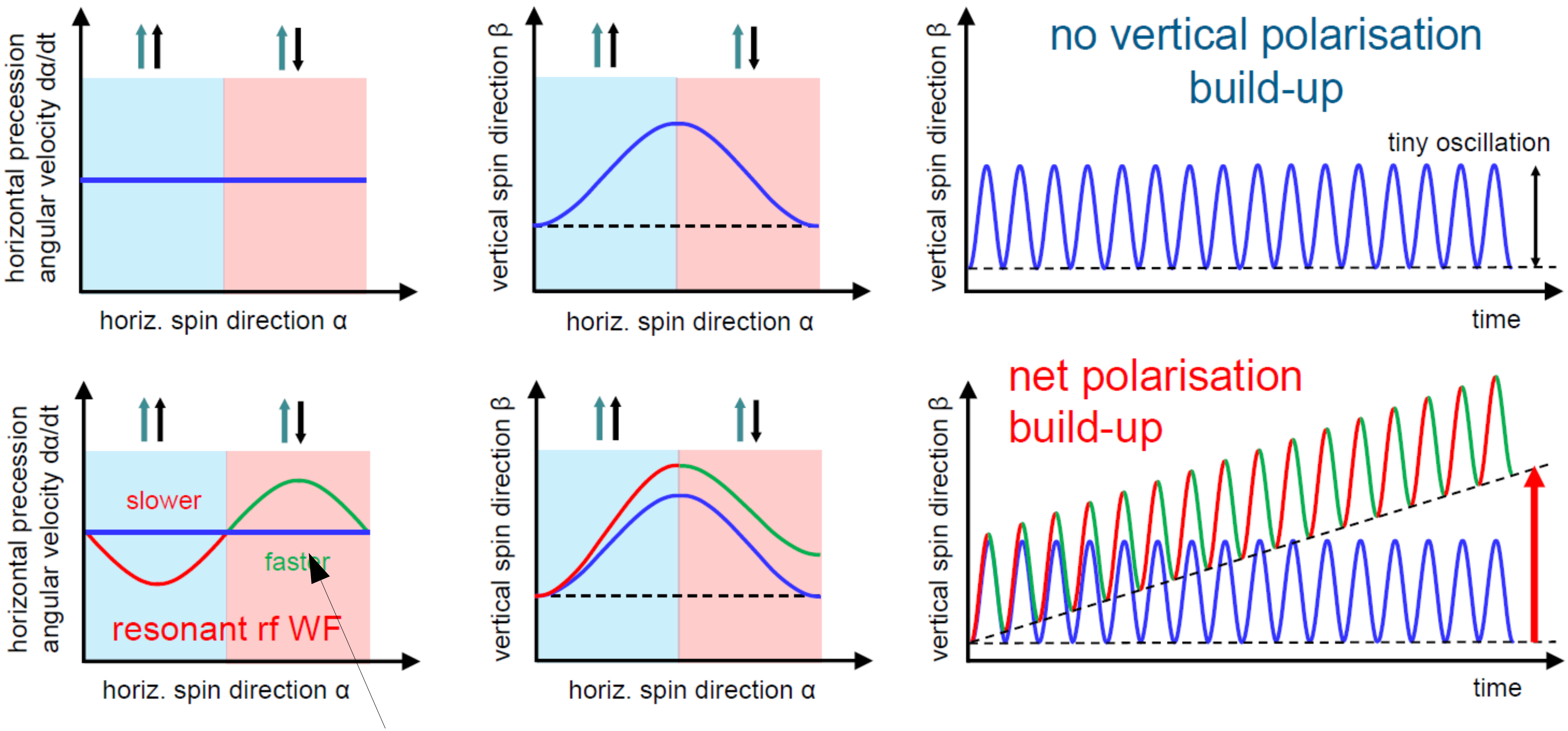
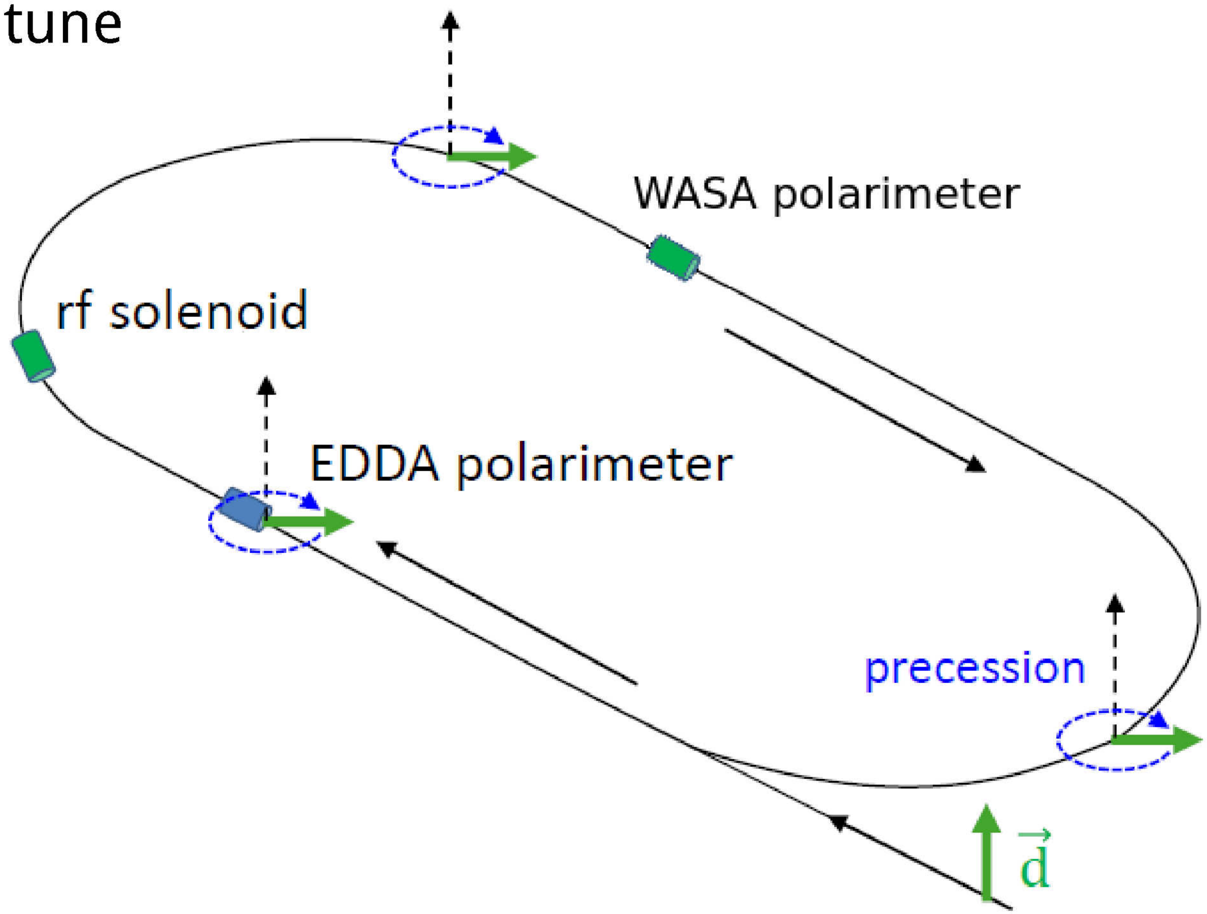


Wien Filter has to be always **in phase** with the horizontal spin precession!

ACTIVITY AT COSY

Jülich Electric Dipole moment Investigations (JEDI)

- Precise determination of spin tune
  Phys. Rev. Lett. 115, 094801 (2015)
- Spin coherence time
  Phys. Rev. Lett. 117, 054801 (2016)
- Phase lock of spin precession
  Phys. Rev. Lett. 119, 014801 (2017)
- Wien filter commissioning
- Polarimetry development
- Beam instrumentation
- Spin-tracking simulations

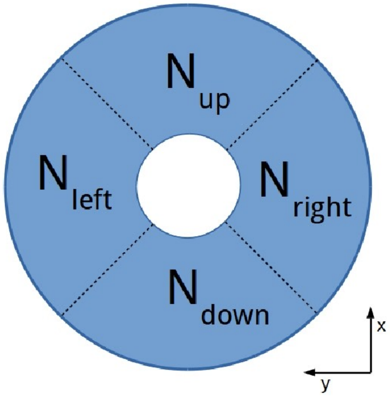


http://collaborations.fz-juelich.de/ikp/jedi/

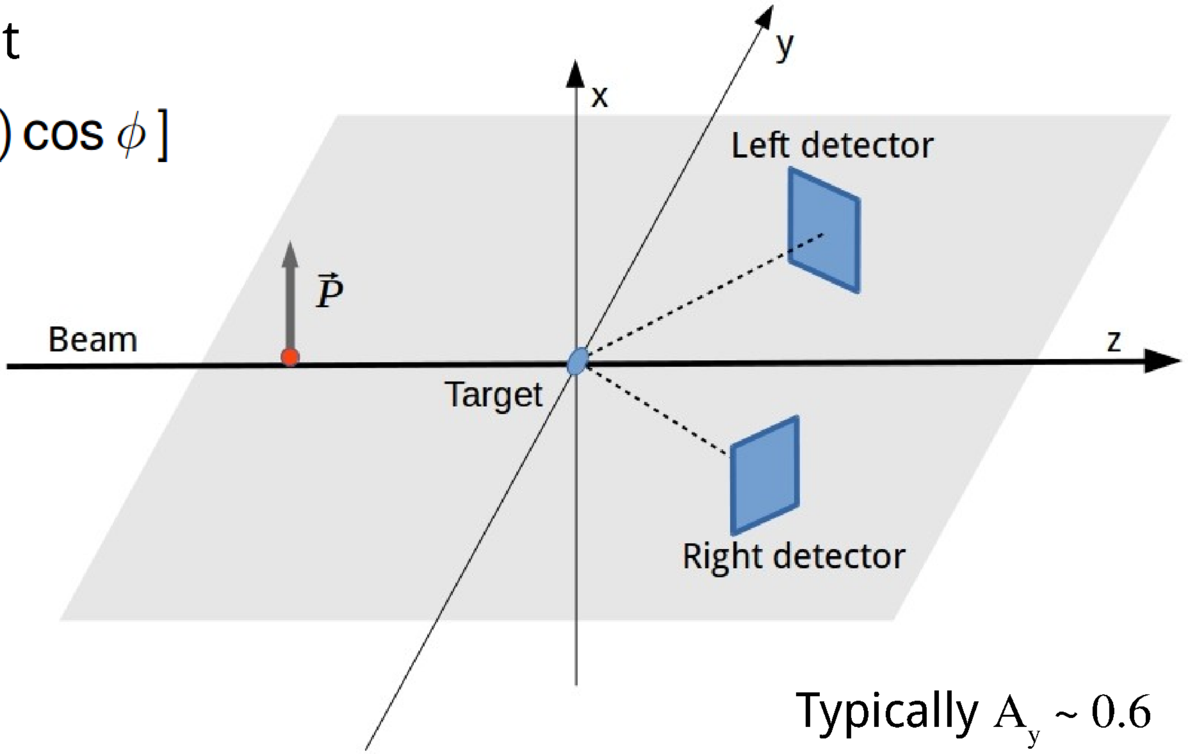
POLARIZATION MEASUREMENT

Scattering from Carbon target

$$\sigma^{pol}(\theta,\phi) = \sigma_0(\theta)[1 + \frac{3}{2} P A_y(\theta) \cos\phi]$$



2π detector - “beam” view



Typically $A_y \sim 0.6$

Right/Left asymmetry ∝ vertical component of polarization P_y

$$\epsilon_{LR} = \frac{N_L - N_R}{N_L + N_R} = P_y A_y$$ ➡ EDM signal appears here

Up/Down asymmetry ∝ horizontal component of polarization P_x

$$\epsilon_{UD} = \frac{N_U - N_D}{N_U + N_D} = P_x A_y$$ ➡ Needed to maintain “frozen spin” condition

POLARIZATION MEASUREMENT

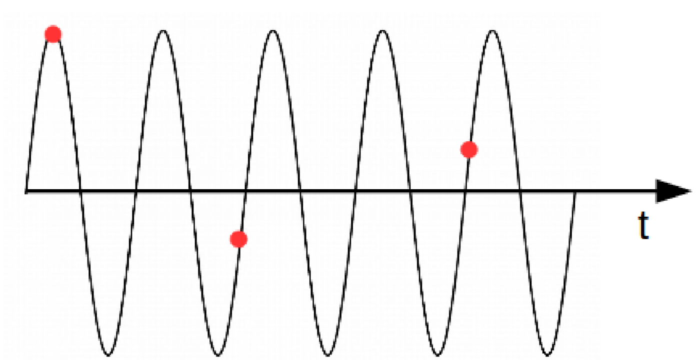
$$\nu_s = \frac{\text{spin revolutions}}{\text{turn}} \approx G\gamma \approx -0.16$$

Deuteron spin precesses with ~ 120 kHz!

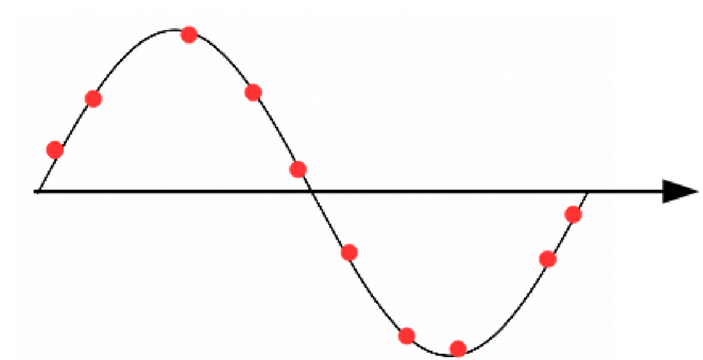
Detector signal and measured asymmetry oscillates

$$\epsilon_{UD} = \frac{N_U - N_D}{N_U + N_D} = P_x A_y \sin(2\pi \cdot f_{\text{prec}} t) = P_x A_y \sin(2\pi \cdot \nu_s n_{turn})$$

With event rates ~ 5000 s^{-1} we have ~ 1 hit / 25 precessions



Too few polarimeter events to resolve oscillation directly!

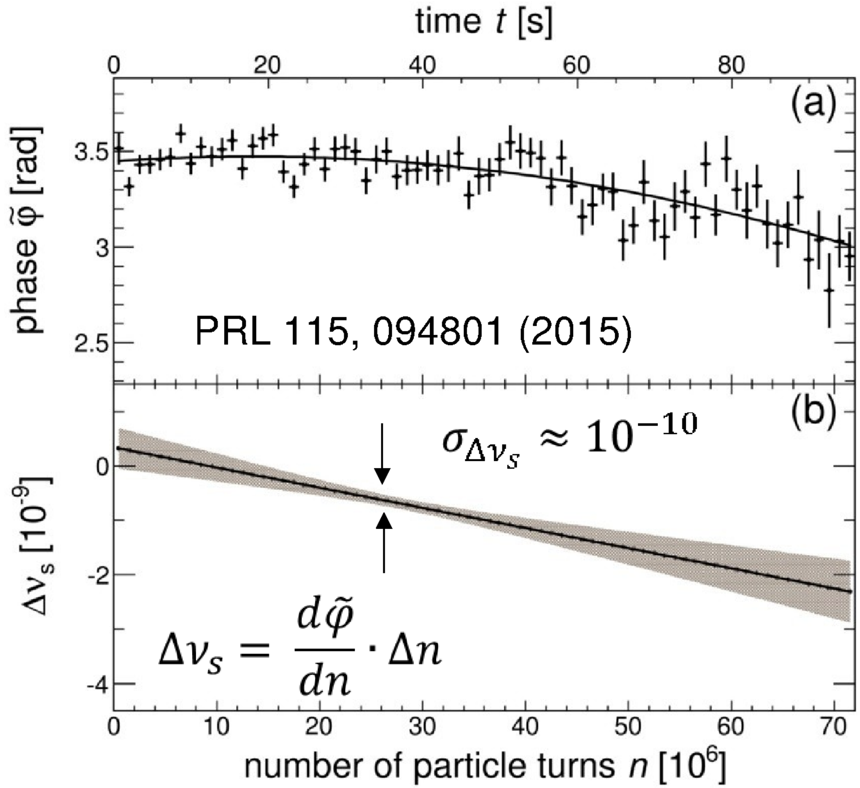


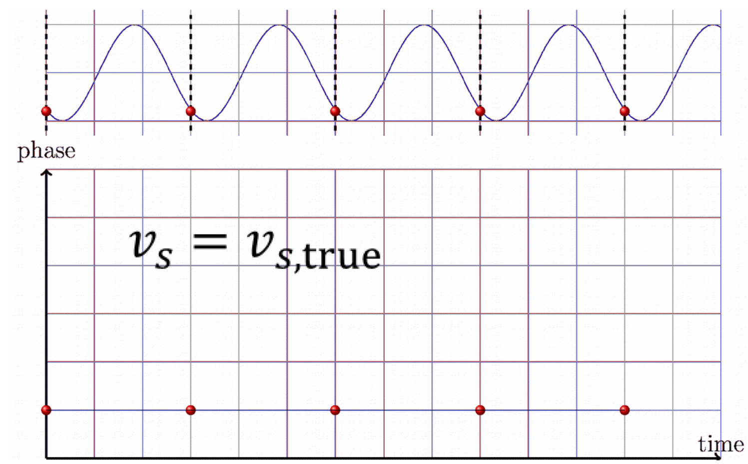
Map events to one cycle

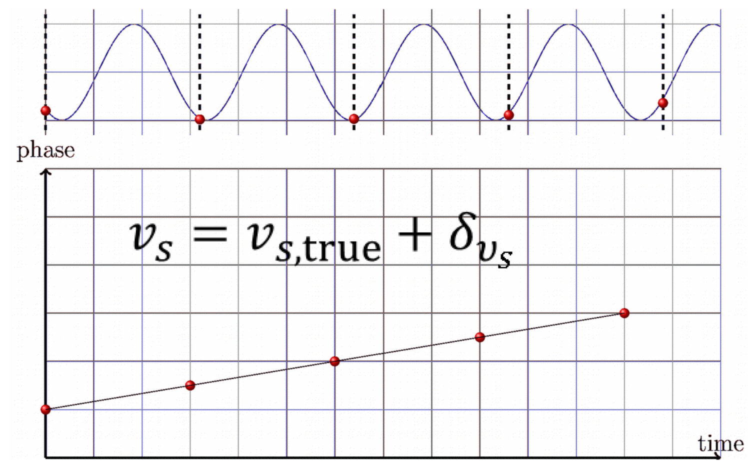
Phys. Rev. ST Accel. Beams 17, 052803 (2014)

PRECISE SPIN TUNE MEASUREMENT

Monitoring phase of asymmetry with fixed spin tune







Relative precision:
Muon (g-2): ~ 10^{-6} Deuteron (JEDI): ~10^{-9}
Much longer measurement: 600µs vs 100 s

Precise determination of G impossible:
Ring imperfections ➡ MDM rotations about non-vertical axes

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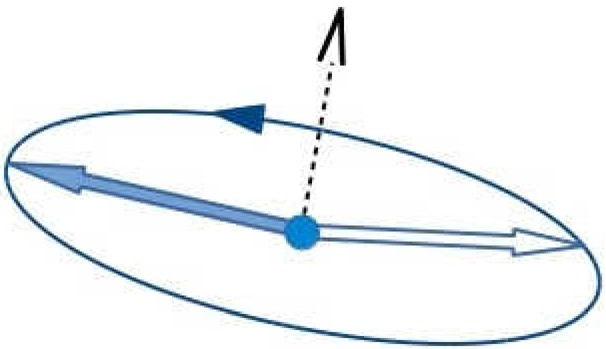
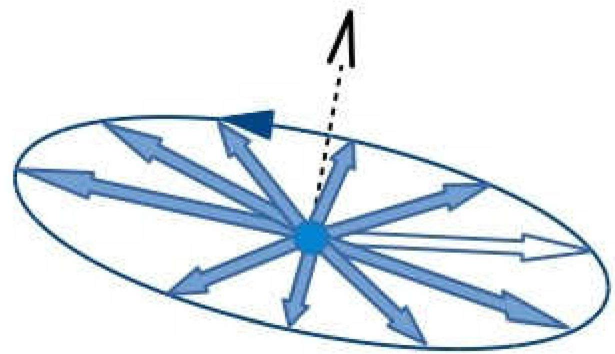
SPIN COHERENCE TIME

Beginning of measurement



All spin vectors aligned

After some time

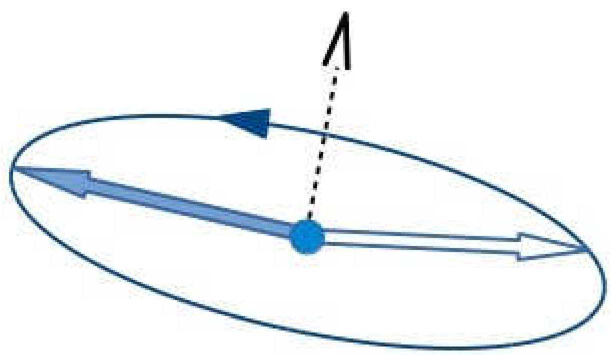


Spin vectors all out of phase

Polarization vanishes → measurement time limited

SPIN COHERENCE TIME

Beginning of measurement



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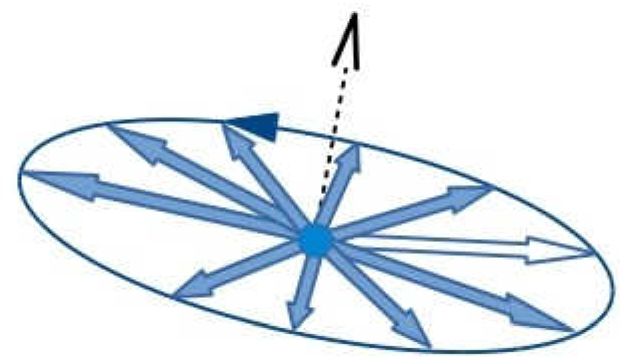
After some time



Spin vectors all out of phase

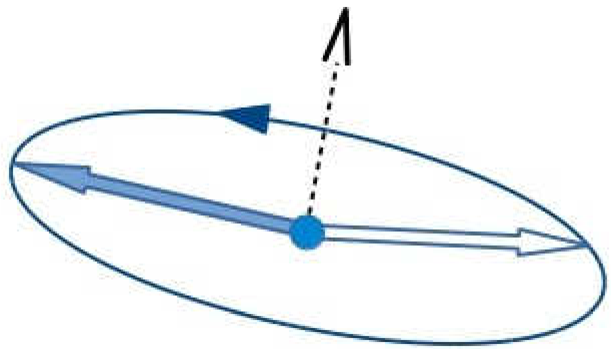
Polarization vanishes → measurement time limited

$$\frac{\Delta\gamma}{\gamma} = \beta^2 \frac{\Delta p}{p} \approx 10^{-4} = \frac{\Delta\nu}{\nu} \quad \Longrightarrow \quad \Delta\varphi \approx 60\ {}^{\mathrm{rad}}/_{\mathrm{s}}$$

- unbunched beam: $\frac{\Delta\gamma}{\gamma} \approx 10^{-5}$ $\Longrightarrow$ decoherence in < 1s
- bunching: eliminate effects on $\frac{\Delta p}{p}$ in 1st order → $\tau \approx 20$ s
- correcting higher order effects using sextupoles
  and (pre-) cooling → $\tau \approx 1000$ s

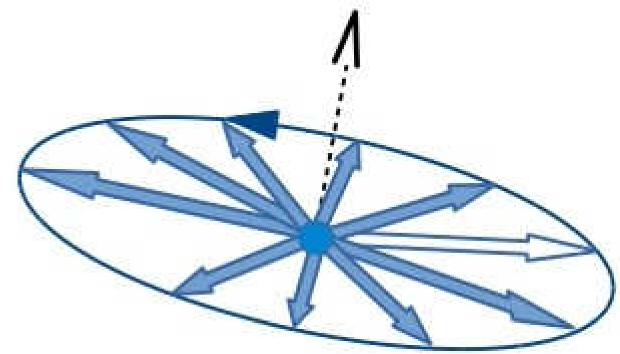
SPIN COHERENCE TIME

Beginning of measurement

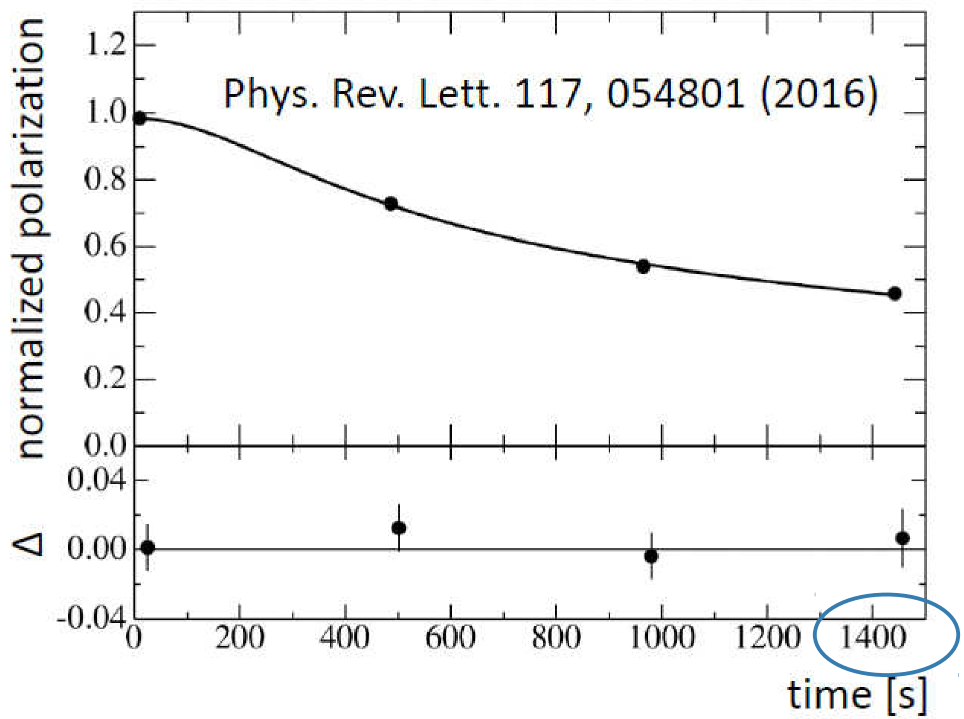


All spin vectors aligned

After > 1000 s



Spin vectors all out of phase

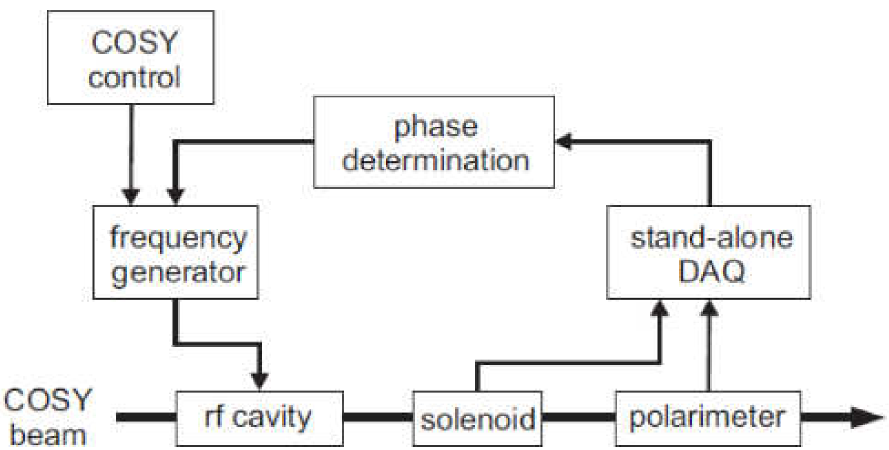


CONTROLLING SPIN DIRECTION

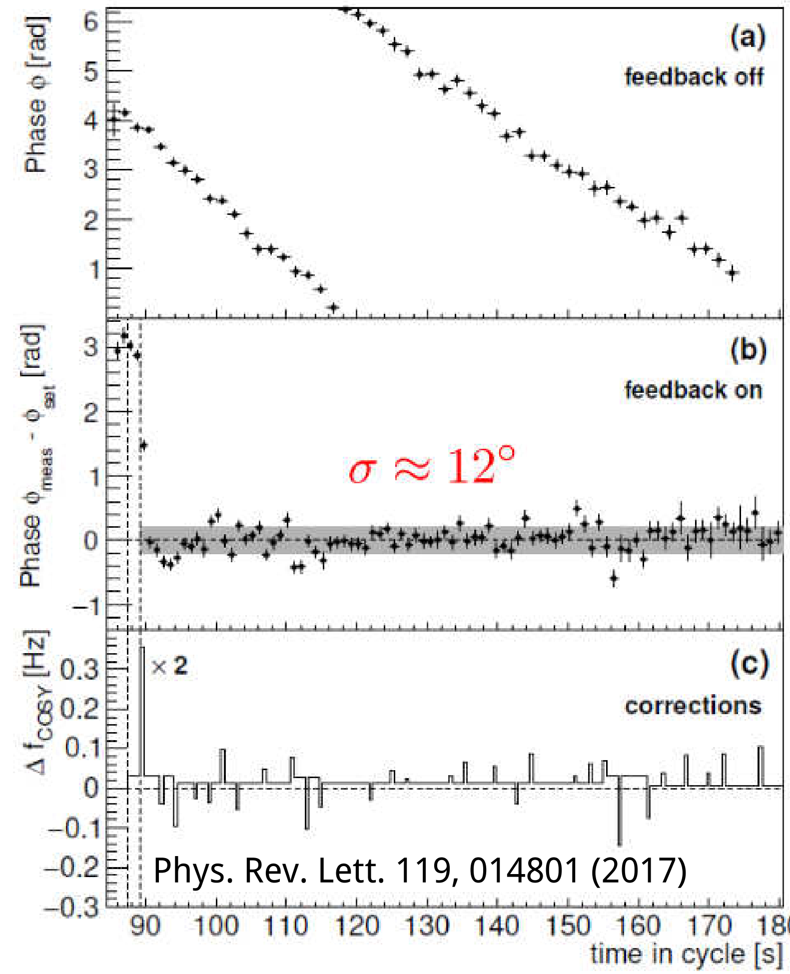
Feedback system

Goal: Maintain resonance frequency and phase between spin precession and Wien filter

1st test at COSY:
control spin tune via COSY rf: $\nu_s = G\gamma$



Now:
We change directly Wien filter frequency!



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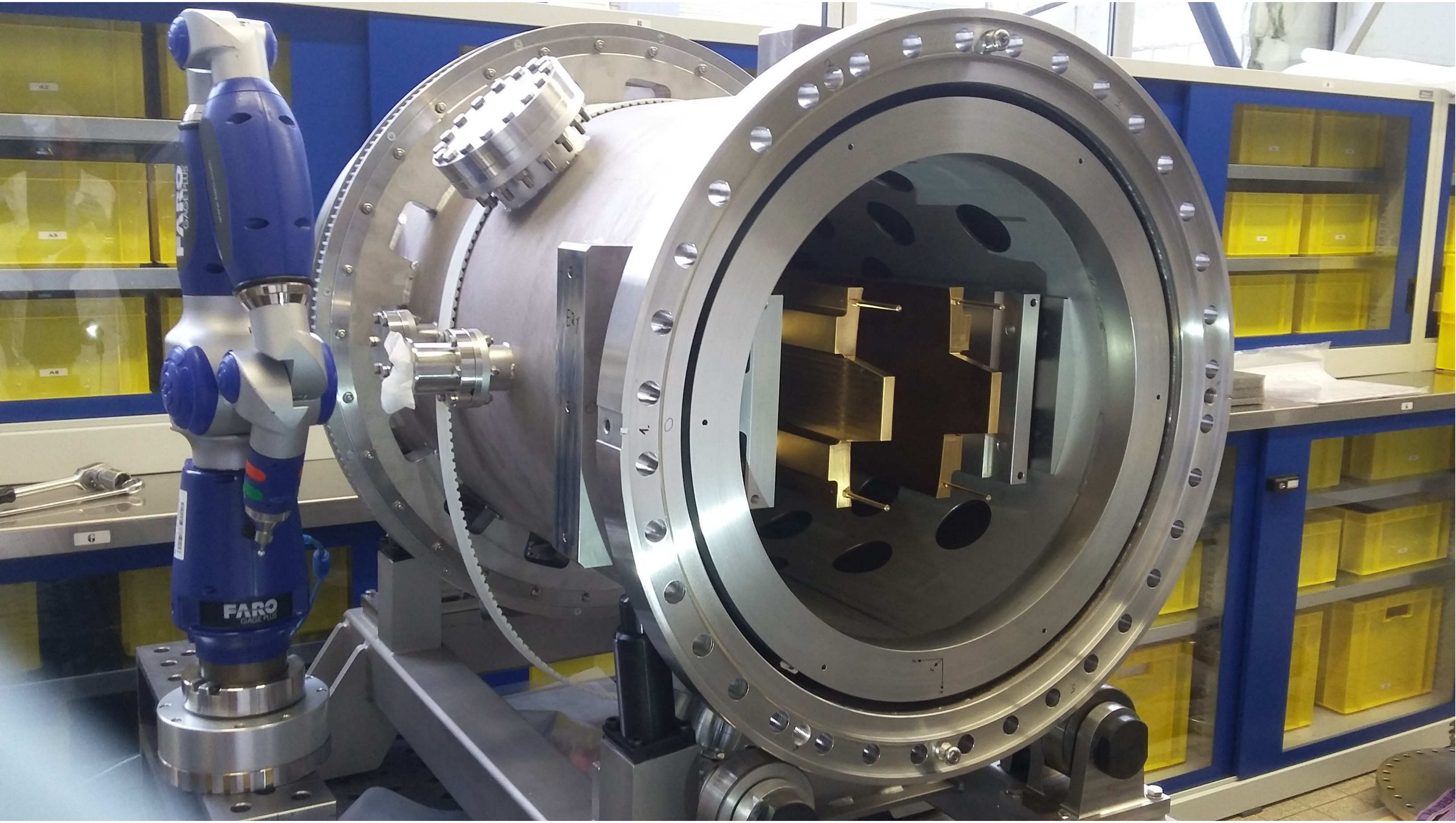
WIEN FILTER COMMISSIONING



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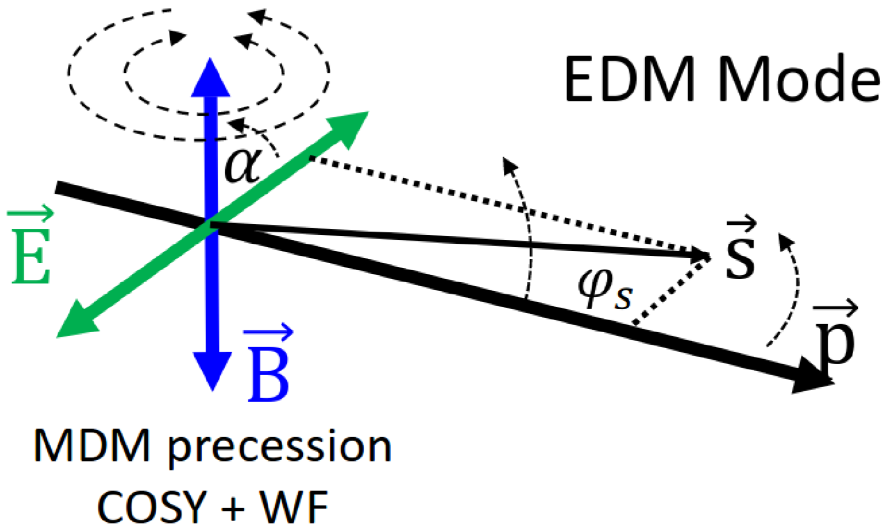
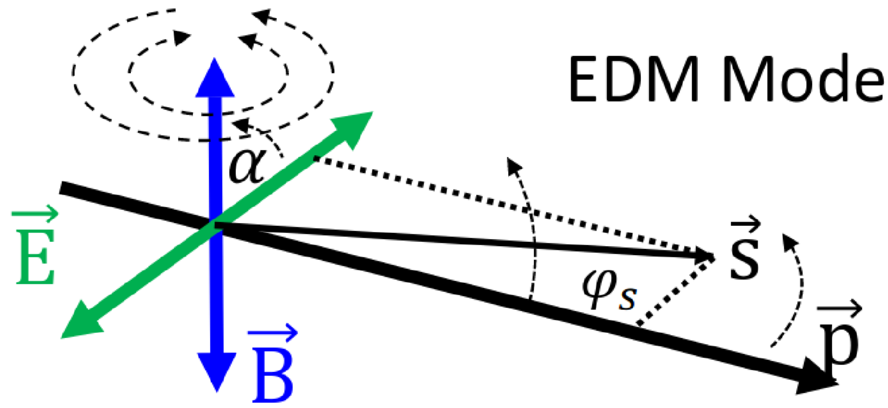
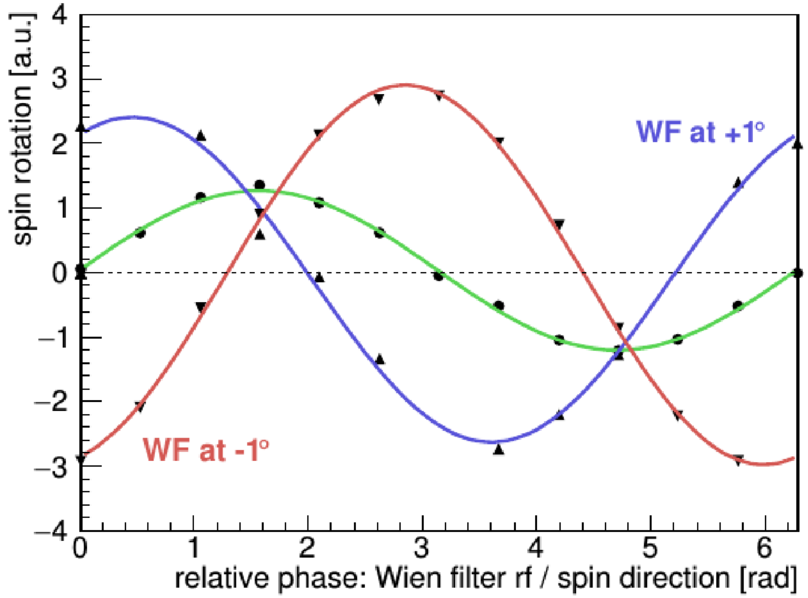
EDM MODE



WIEN FILTER COMMISSIONING

EDM MODE

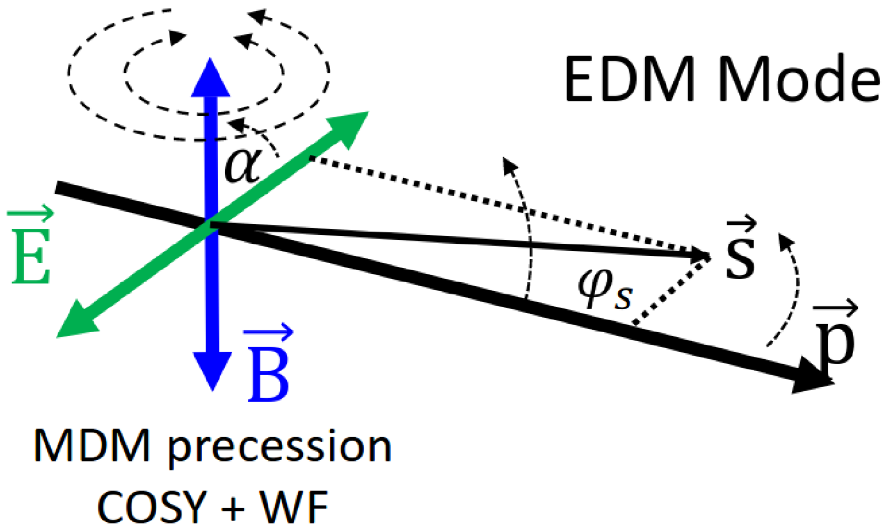


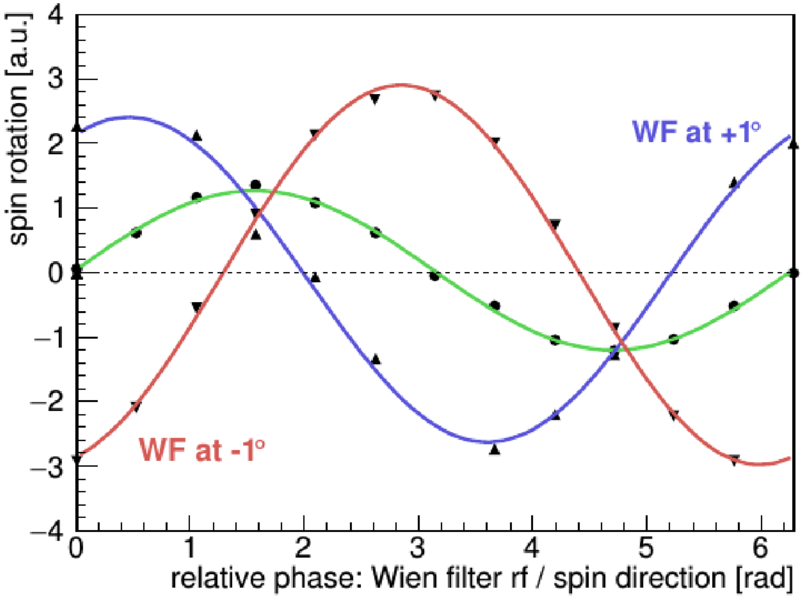


We see **vertical polarization buildup - EDM-like signal**

WIEN FILTER COMMISSIONING

EDM MODE





We see **vertical polarization buildup - EDM-like signal**

Two **systematic** contributions:

1. Residual, radial magnetic field from WF

- effect equivalent to WF rotation

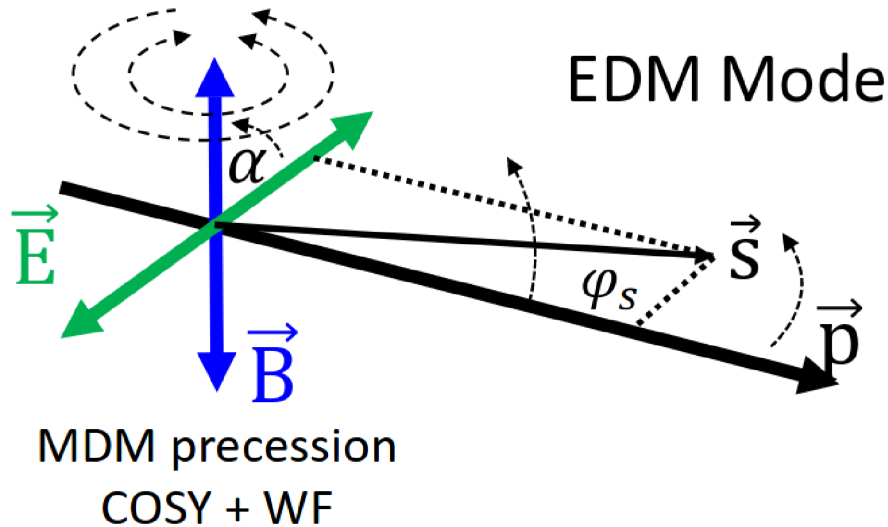
2. Field imperfections in COSY

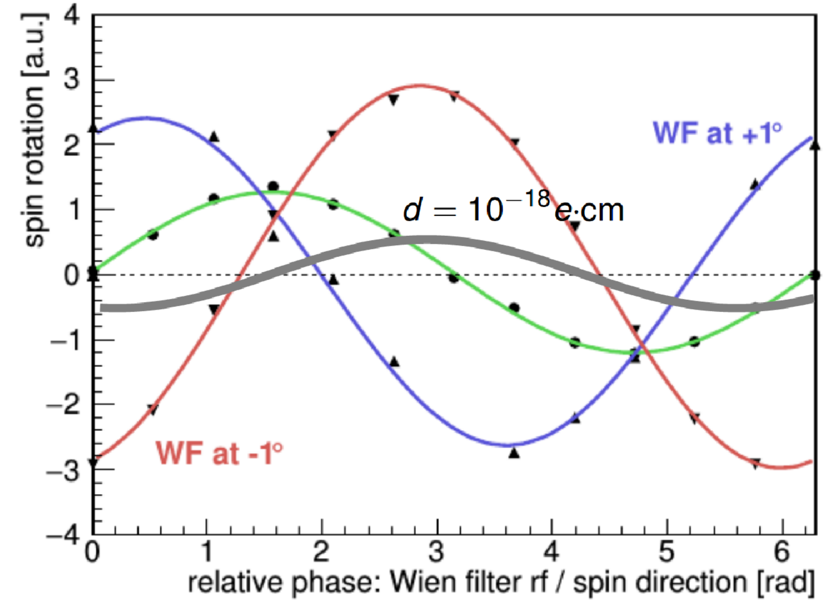
- transverse contribution: equivalent to WF rotation
- longitudinal contribution: equivalent to additional static solenoid field

Stability of COSY conditions within 24 hours

WIEN FILTER COMMISSIONING

EDM MODE





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Stability of COSY conditions within 24 hours

OUTLOOK

2019 COSY

1st deuteron EDM measurement
Sensitivity: ~ 10^{-19} e·cm

Prototype ring

- Proof of principle
- Test deflectors/instrumentation
- Check lifetime
- Test CW/CCW operation
- Test frozen spin (additional B-field at low energy)

? Dedicated ring

Highly sensitive EDM measurement

SUMMARY

- EDMs of elementary particles key for understanding sources of CP violation
  - ➔ explanation of matter – antimatter imbalance
- Extremely ambitious measurement for charged particles
- Preparations for proof-of-principle experiment at COSY
  - ➔ Extended R&D program
- First measurement of deuteron EDM in progress

THANK YOU!

http://collaborations.fz-juelich.de/ikp/jedi/

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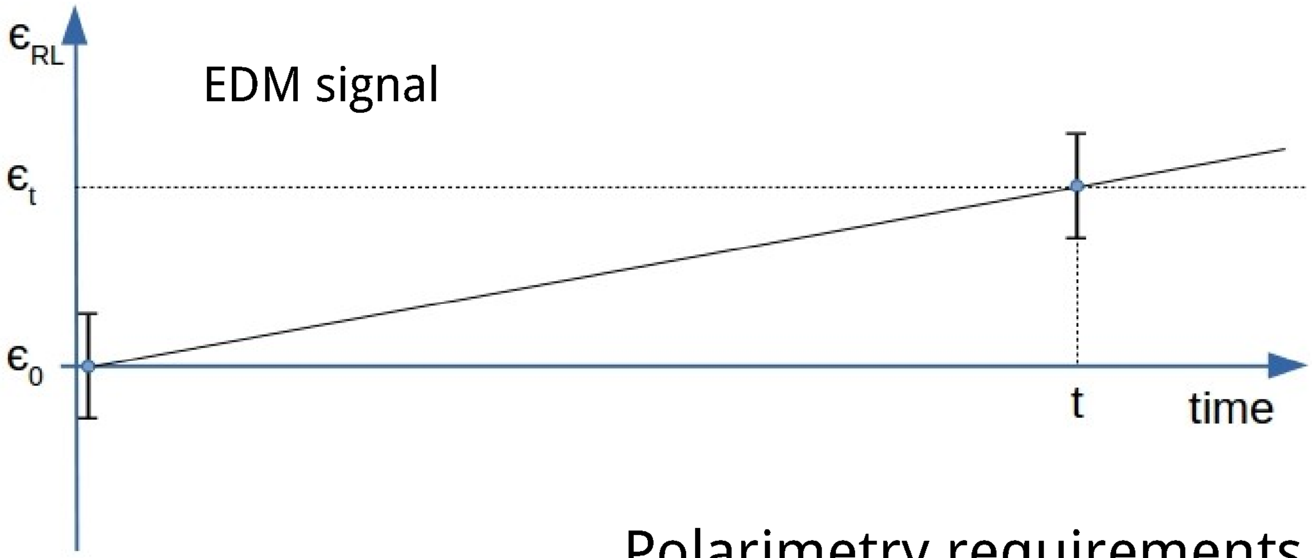
BACKUP

POLARIMETRY FOR AN EDM EXPERIMENT

Challenge: measurement of **tiny polarization build-up**



For proton EDM ~ 10^{-29} e·cm and ~ 1year of measurement

$$\Delta\epsilon_{LR} = \epsilon_t - \epsilon_0$$
$$= \Delta P_y A_y \approx 10^{-6}$$

Systematics count!

Polarimetry requirements

Long term reproducibility:
→ Continuous measurement for a long time

$$\delta\epsilon_{LR}(\text{stat}) \propto \frac{1}{\sqrt{N}|A_y|} = \frac{1}{\sqrt{\text{FoM}}}$$

Minimization of asymmetry error:
→ Maximization of FoM

Figure of Merit

Efficiency   High A_y

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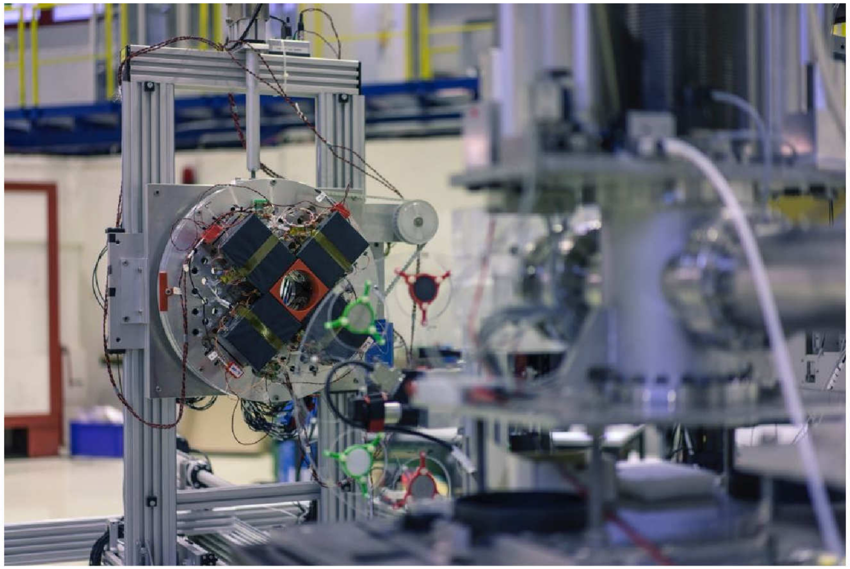
ACTIVITY AT COSY

Jülich Electric Dipole moment Investigations (JEDI)

R&D with towards first proof-of-principle EDM experiment for deuterons and protons



Polarimetry-group activity:
- Development of dedicated polarimeter based on LYSO crystals
- **Database experiment with WASA detector**

Motivation:
- Optimal configuration of the polarimeter

Goal: A_y, A_{yy}, $d\sigma/d\Omega$ for
- dC elastic scattering
- main background reactions (deuteron breakup)

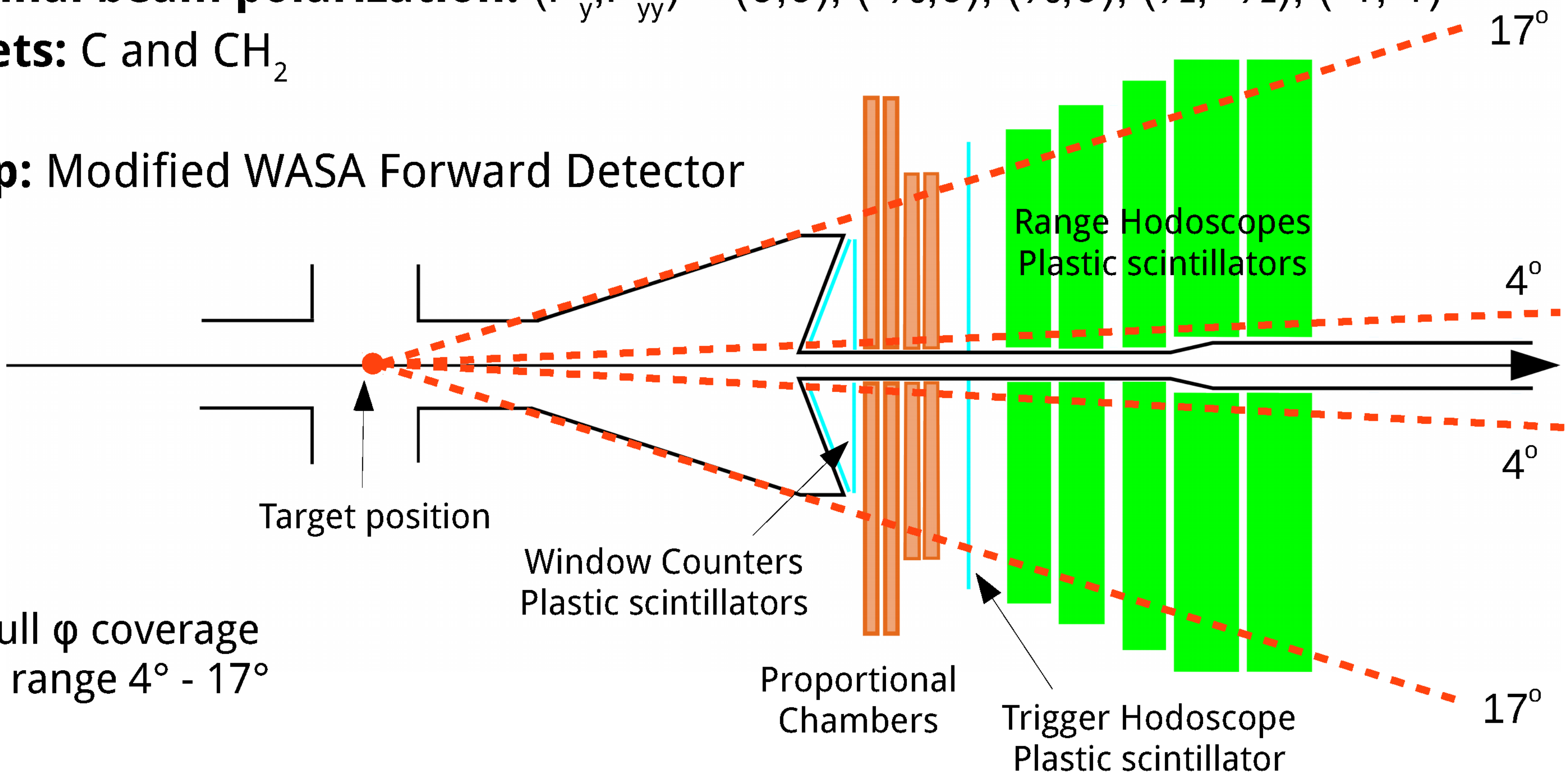
http://collaborations.fz-juelich.de/ikp/jedi/

DEUTERON DATABASE EXPERIMENT WITH WASA

Detector Setup

Beamtime in November 2016 (2 weeks)
Deuteron energies: 170, 200, 235, 270, 300, 340, 380 MeV
Nominal beam polarization: (P_y, P_{yy}) = (0,0), (-⅔,0), (⅔,0), (½, -½), (-1, 1)
Targets: C and CH_2

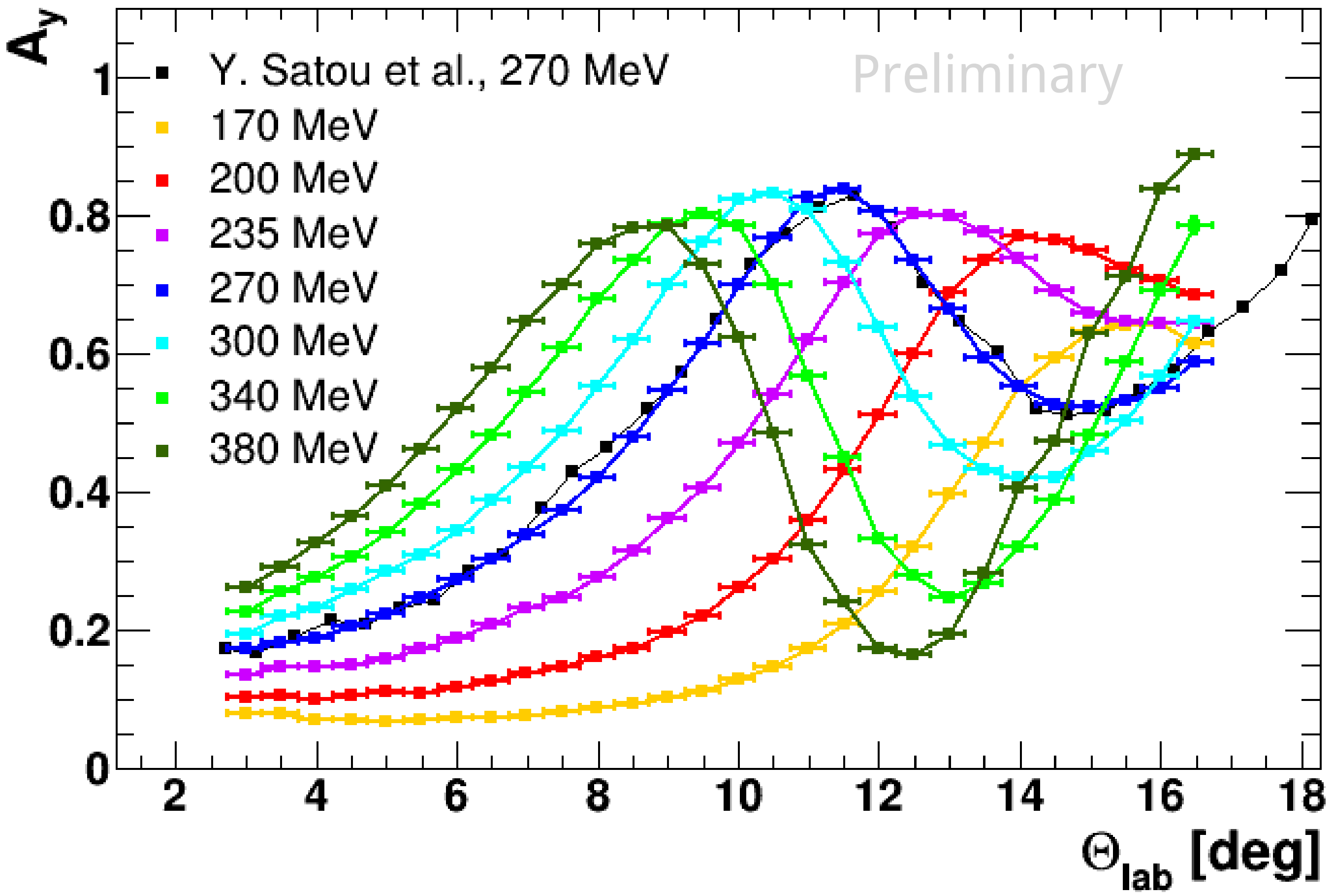
Setup: Modified WASA Forward Detector



- Full φ coverage
- θ range 4° - 17°

DATABASE EXPERIMENT WITH WASA

Analyzing power for elastic dC scattering



POLARIMETRY

Detector signal

$$N^{up,down} = 1 \pm PA\sin\left(2\pi \cdot f_{\mathrm{prec}} t\right)$$
$$= 1 \pm PA\sin(2\pi \cdot \nu_s\, n_{\mathrm{turns}})$$

P: polarisation, A: analysing power

Asymmetry

$$\varepsilon = \frac{N^{up} - N^{down}}{N^{up} + N^{down}} = PA\sin(2\pi \cdot \nu_s\, n_{\mathrm{turns}})$$

Challenges

- precession frequency $f_{\mathrm{prec}} \approx 120$ kHz
- $\nu_s \approx -0.16$ $\longrightarrow$ 6 turns / precession
- event rate ≈ 5000 s^{-1} $\longrightarrow$ 1 hit / 25 precessions

$\longrightarrow$ no direct fit of the rates

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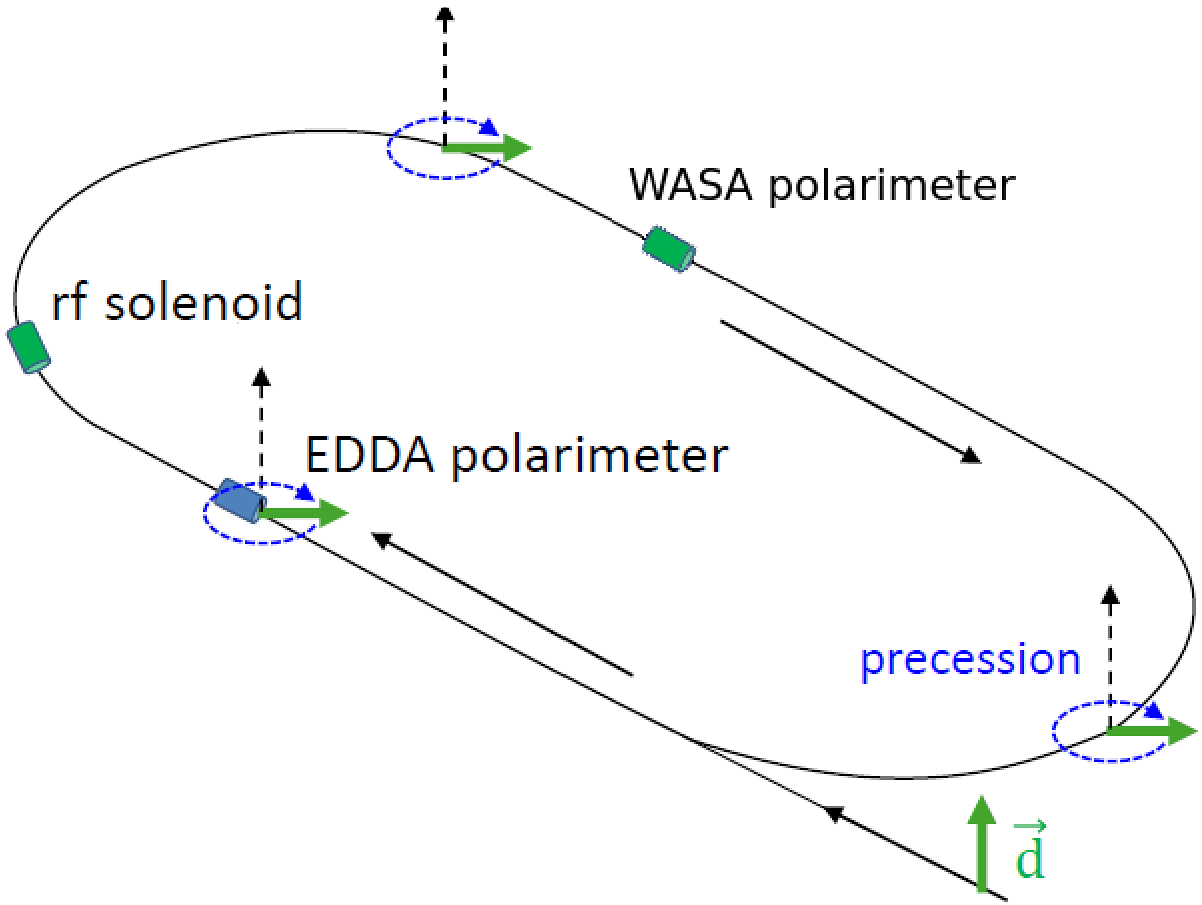
R&D AT COSY

EDMs of charged hadrons: p, **d**

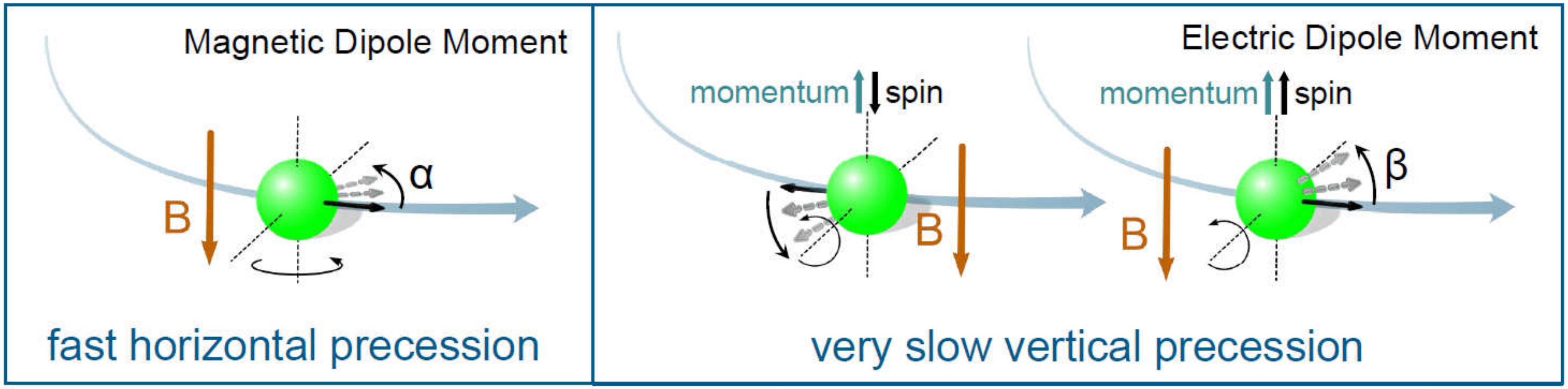
R&D with deuterons
p = 1 GeV/c
G = -0.14256177(72)
ν_s ≈ -0.161 f ≈ 120 kHz

study spin tune $\nu_s = \frac{|\vec{\Omega}|}{|\vec{\omega}_{\mathrm{cycl}}|} = \gamma G$

→ phase advance per turn

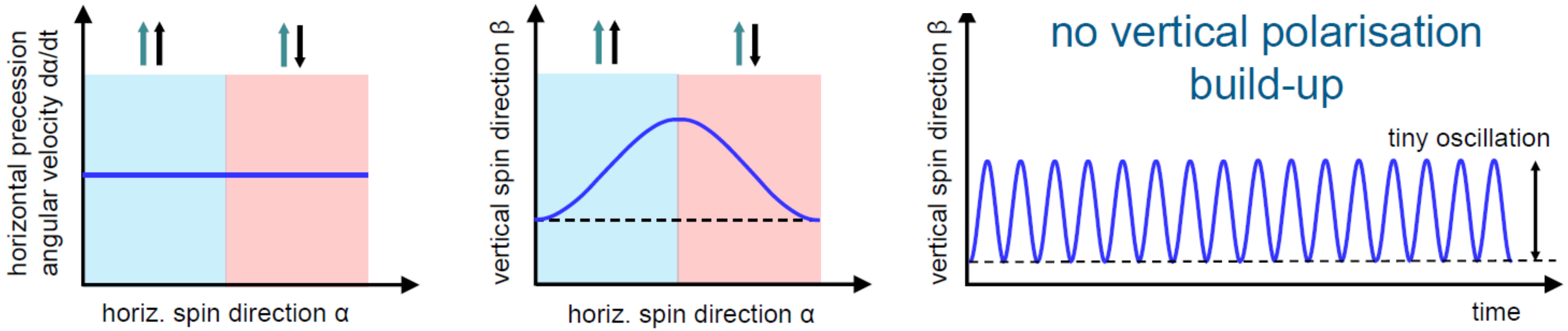


WIEN FILTER METHOD



E* field tilts spin due to EDM
50% of time up
50% of time down

$$\frac{d\vec{S}}{dt} \propto \left(G\vec{B} + d\frac{m_0 c}{q\hbar S}\vec{\beta} \times \vec{B} \right) \times \vec{S}$$



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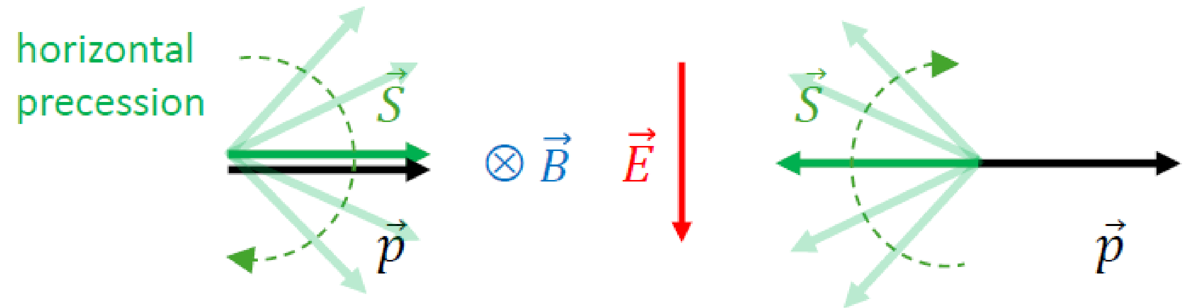
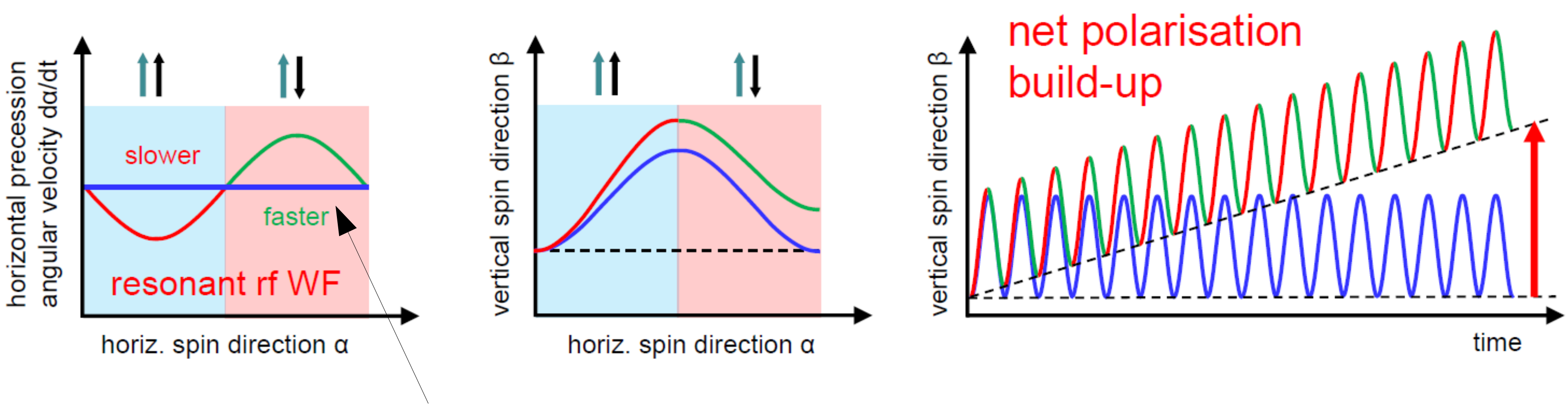
WIEN FILTER METHOD

- Wien Filter: introduces B and E field oscillating with radio frequency
- Lorentz force vanishes: no effec on EDM rotation
- **Effect: Adds extra horizontal precession**



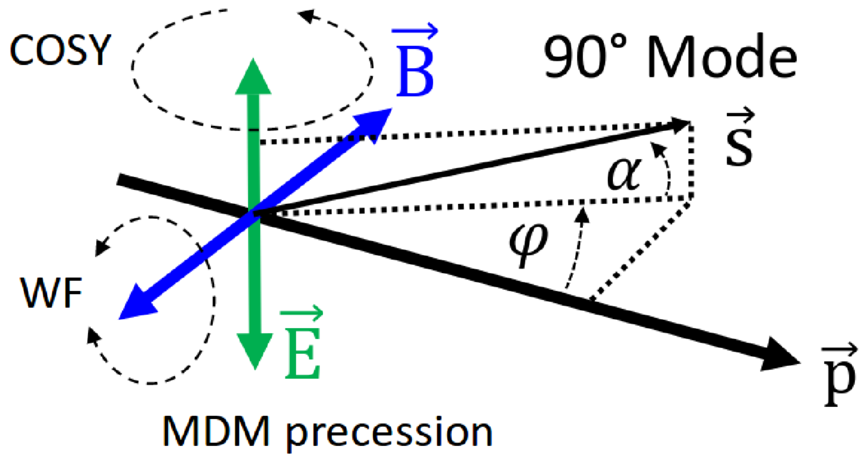


Wien Filter has to be always **in phase** with the horizontal spin precession!

Feedback system developed and tested: Phys. Rev. Lett., 119, 014801 (2017)
Resonant frequency controlled, precession of spin phase locked

WIEN FILTER COMMISSIONING – 90° MODE

SPIN ROTATIONS WITH PHASE LOCK

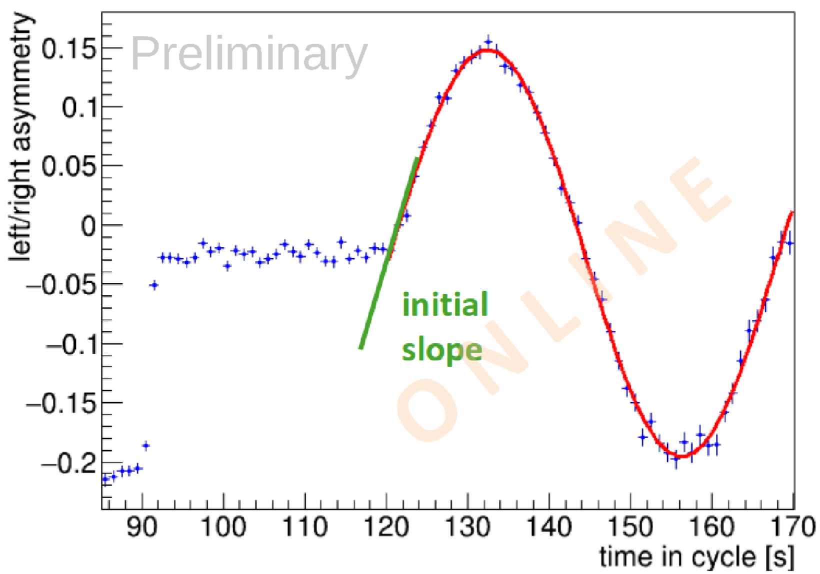


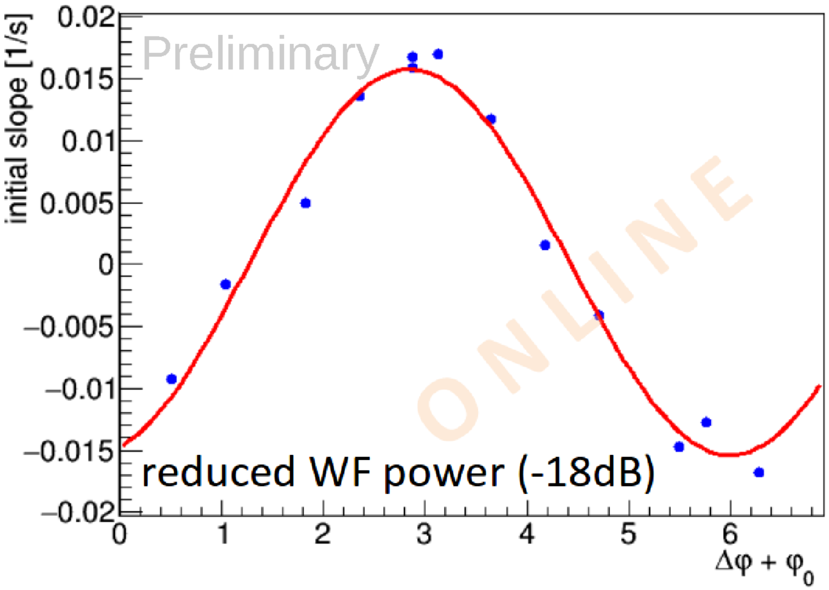
$$\varphi(t) = 2\pi\, \nu_s f_C t$$

$$B_{WF}(t) = B_0 \sin(\omega t + \Delta\varphi)$$

Task: maintain $\omega = 2\pi\, |k + \nu_s| f_C$
and fix $\Delta\varphi$

Controlled via WF frequency

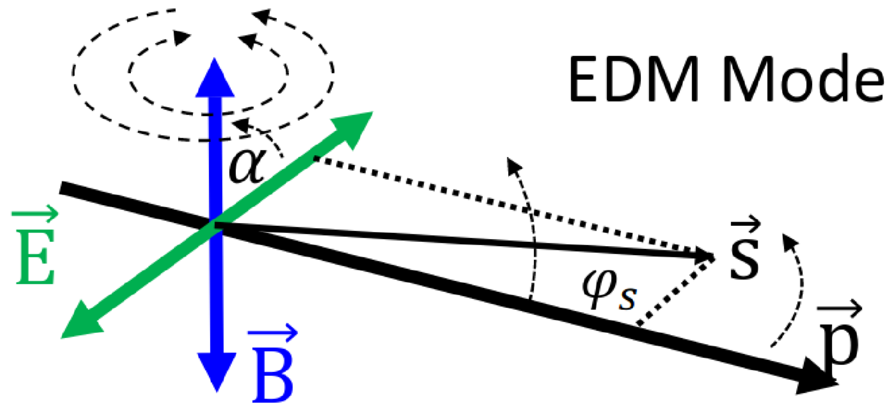


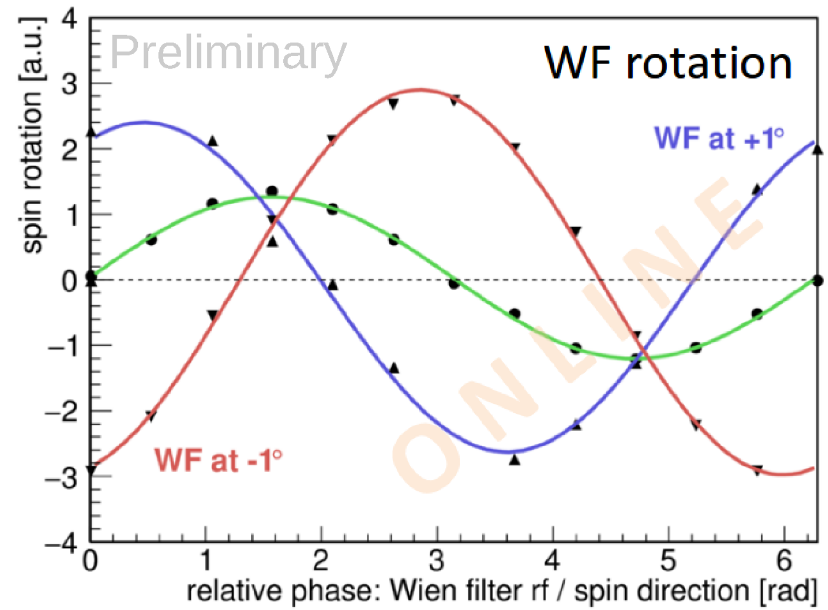


Spin build-up as a function of phase ~ sinΔφ → Feedback system works properly!

WIEN FILTER COMMISSIONING – 0° MODE

SPIN ROTATIONS WITH PHASE LOCK





We see **vertical polarization buildup - EDM-like signal**

Two **systematic** contributions:

1. Residual, radial magnetic field from WF

- effect equivalent to WF rotation

2. Field imperfections in COSY

- transverse contribution: equivalent to WF rotation
- longitudinal contribution: equivalent to additional static solenoid field

The measurement shows the stability of COSY conditions within 24 hours

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