MEASUREMENT OF ELECTRIC DIPOLE MOMENTS AT STORAGE RINGS
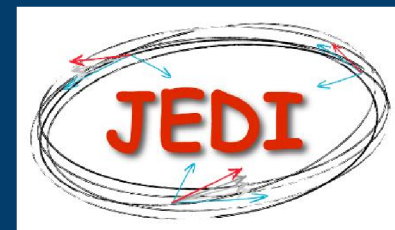
VOLKER HEJNY, INSTITUT FÜR KERNPHYSIK

FORSCHUNGSZENTRUM JÜLICH

Why are we here?

Big Bang

energy
⬇
matter &
antimatter

symmetrie
between
matter &
antimatter

Early Universe
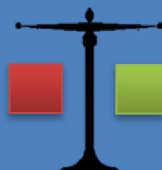
preference of
matter

Sakharov criteria:
- baryon number
  violation
- no thermic
  equilibrium
- $\mathcal{C}, \mathcal{CP}$ violation

matter-antimatter annihilation

Today

ratio
$\dfrac{\text{matter - antimatter}}{\text{radiation}}$

observed
(WMAP 2003)
$(6.14 \pm 0.25)10^{-10}$

galaxies, stars,
planets

⬍

Standard Model
10^{-18}

"empty"
universe

Search for $\mathcal{CP}$ violation beyond
the Standard Model

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Outline

- Electric Dipole Moments
    - What are those?
    - How can they help?
- EDM measurements using storage rings
    - Basic principles
    - Options
- R&D and first measurements at COSY

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

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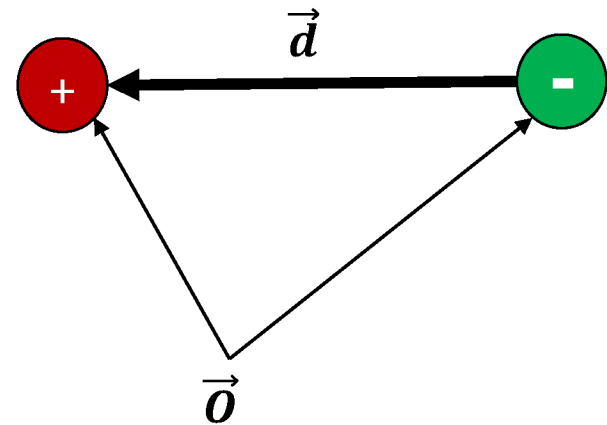
Electric Dipole Moments (EDM)

Classical definition: $\vec{d} = \sum q_i \vec{r}_i$

> charge x distance

Example: water molecule

> charge separation
> ⬇
> electric dipole moment
> $d \approx 4 \times 10^{-9} \, e \, \mathrm{cm}$

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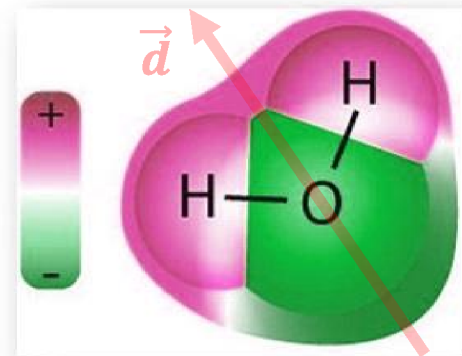
EDMs of elementary particles

$\vec{s}$ spin

$\vec{d}$ electric dipole moment

$\vec{\mu}$ magnetic moment

Transformations w.r.t. $\mathcal{P}$, $\mathcal{T}$

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

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

$$\mathcal{T}:\quad H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$
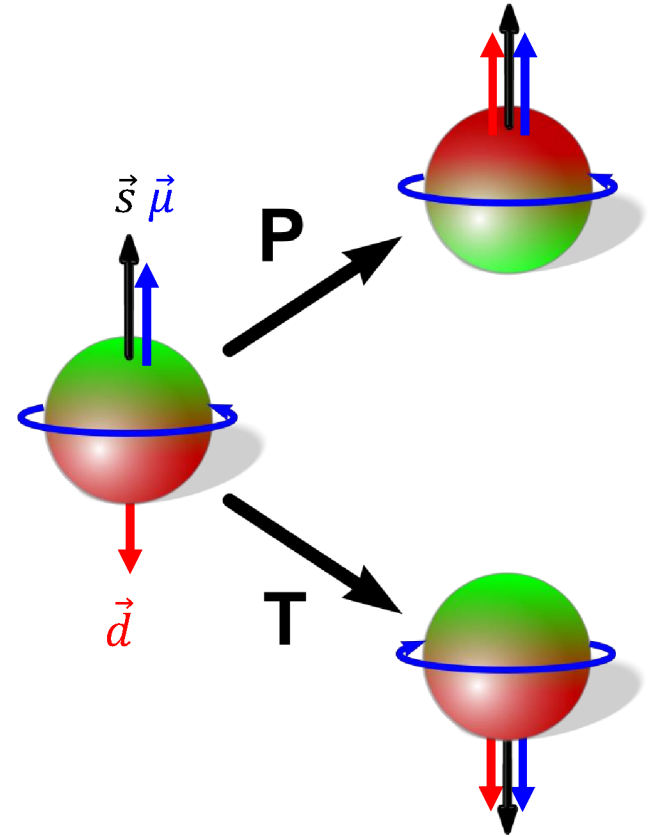
EDM measurements test violation of fundamental symmetries $\mathcal{P}$, $\mathcal{T}$ and CP (via CPT)

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So what is the difference?

elementary particle

EDM violates $\mathcal{P}$, $\mathcal{T}$
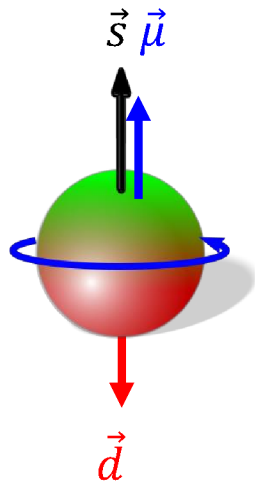
defined parity!

water molecule

EDM allowed
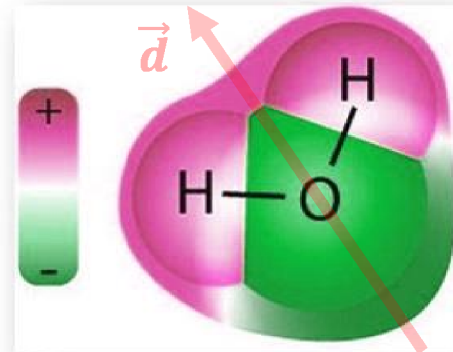
degenerated
ground state
with mixed parity!

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How can that help?

Reminder: excess of matter in the universe

	Standard Modell	Observed
$\dfrac{n_B - n_{\bar{B}}}{n_\gamma}$	$\approx 10^{-18}$	6×10^{-10}

Sakharov (1967): CP violation needed for baryogenesis

New sources of CP violation needed
to explain this mismatch

EDMs as a probe for CP violation beyond the SM

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Sources of CP violation

Standard Model		
weak interaction	CKM matrix	unobservably small EDMs
strong interaction	θ_{QCD}	best limit from neutron EDM $(\lesssim 10^{-10})$ "strong CP problem"
beyond Standard Model		
e.g. SUSY	?	accessible by EDM measurements

Different sources of CP violation result in
a different EDM for different particle types

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Disentangling *CP* violation …
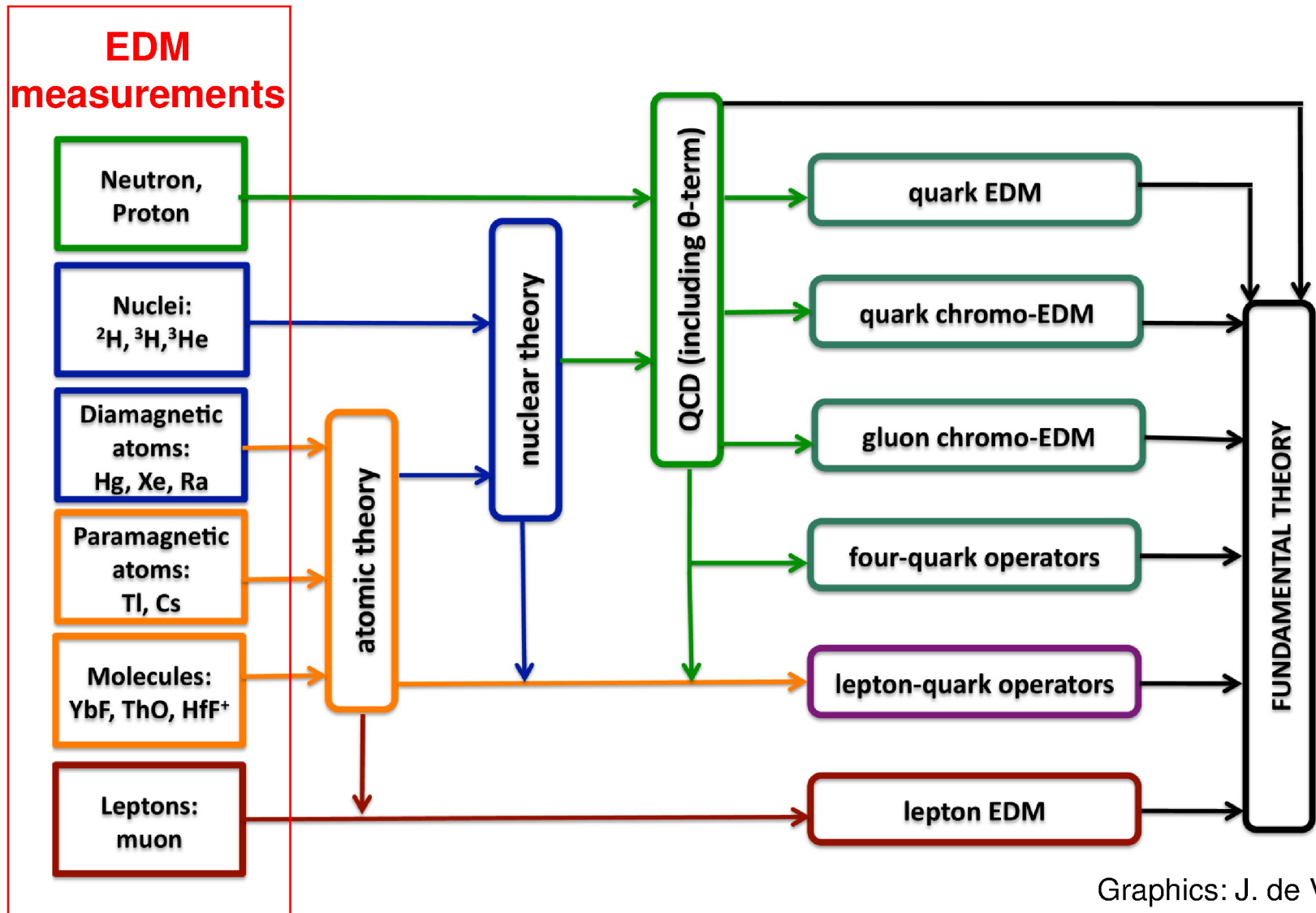
Graphics: J. de Vries

Current EDM limits
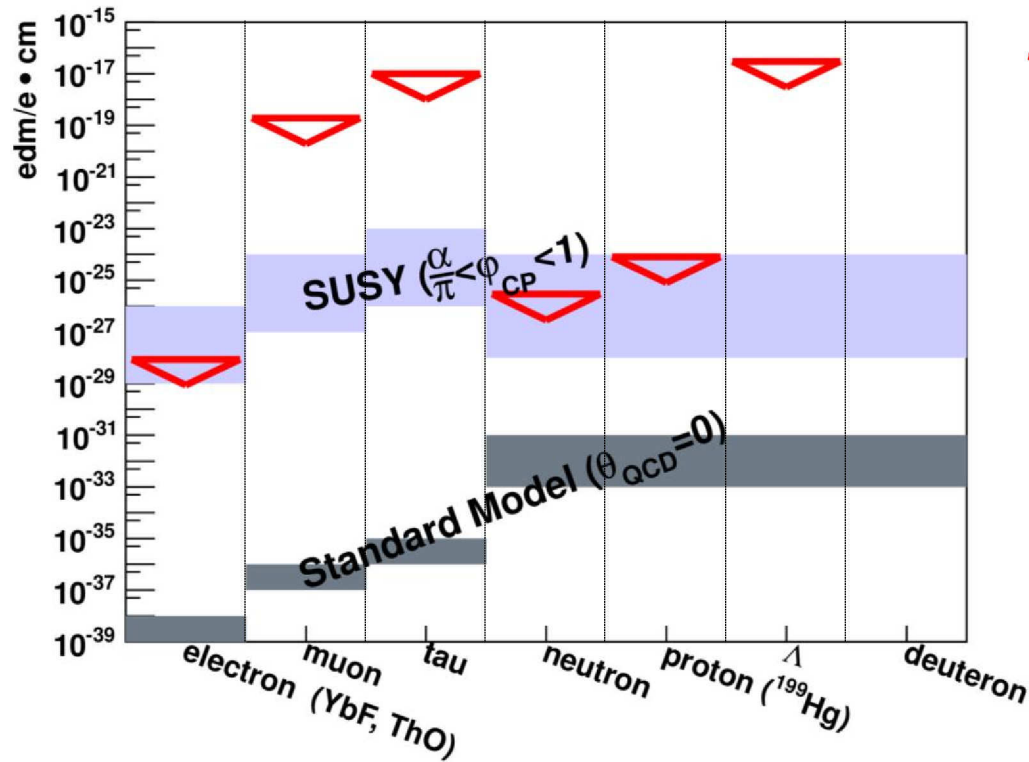
Upper limits

- **proton**
  no direct measurement
- **deuteron**
  no measurement

Here: EDMs of charged particles

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How to measure EDMs?

Common strategy for all EDM measurements:

→ measure interaction of $\vec{d}$ with electric field $\vec{E}$

neutral

no spin

$\vec{E}$ $\vec{E}$
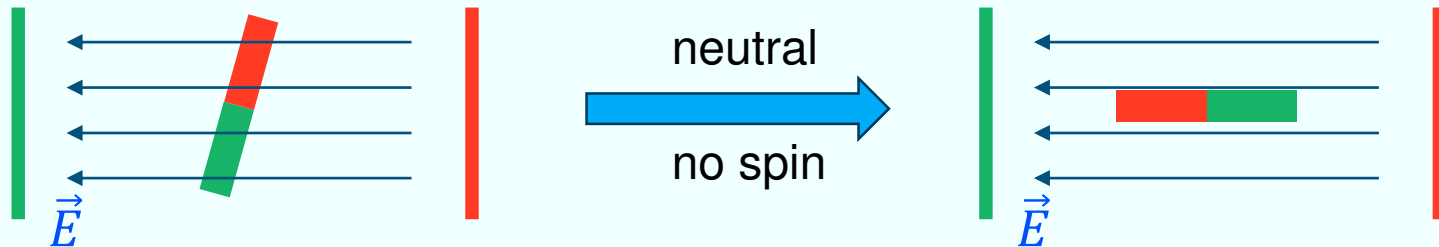
With spin:

→ precession

For charged particles:

acceleration

$\vec{E}$
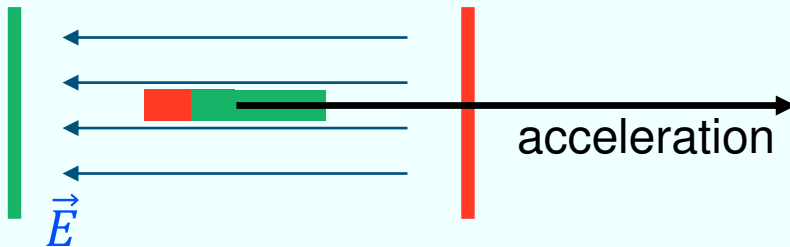
https://www.youtube.com/watch?v=qwM4enslA_k
by Tales Of a Musing Gator

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How to measure EDMs of charged particles?

Electric field accelerates particles
 → use a storage ring

Ideal case:

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

$\vec{S} \parallel \vec{p}$

$\vec{s}$

$\vec{E}$
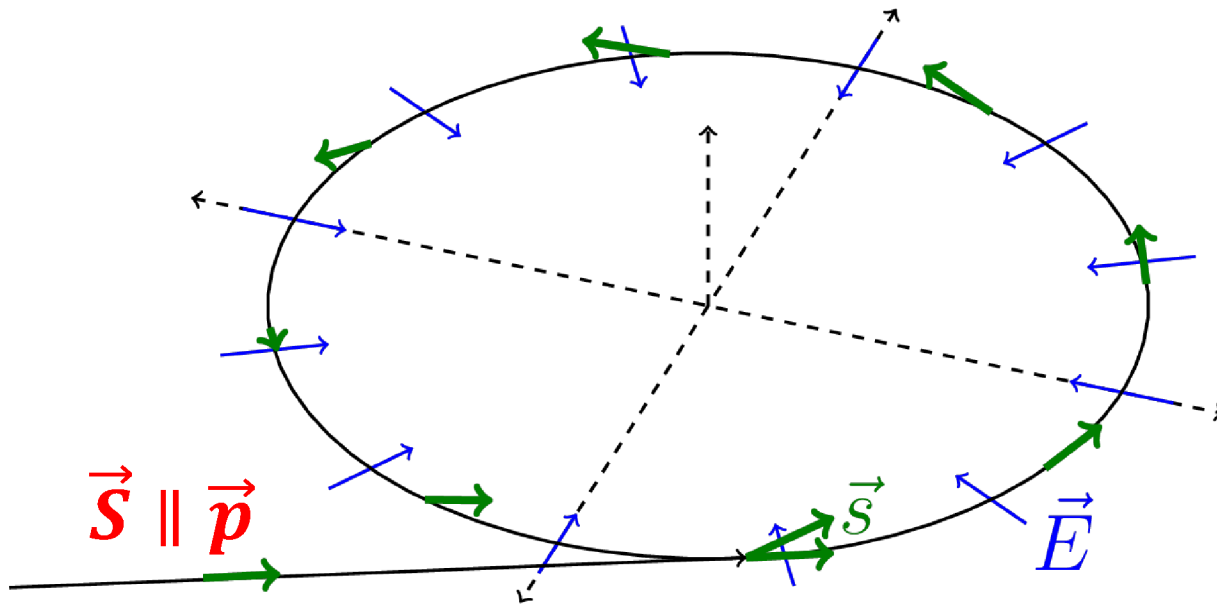
Build-up of vertical polarisation by slow precession

$$s_\perp \propto |d|$$

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"Ad-hoc" boundary conditions

Very slow spin precession	Long measurement times ($t \approx 1000$ s) High electric fields ($E \approx 10$ MV/m) High degree of polarization ($P \approx 0.8$) Precise polarisation measurement (analysing power $A \approx 0.6$, acc. $f \approx$ 0.005)
Particle ensemble ($N \approx 4 \times 10^{10}$ per fill)	All particles must act identically All spins need to be aligned ("spin coherence time")
In-plane polarisation ‖ momentum	Control spin motion at high precision
Magnetic moment causes fake rotations	High field quality Magnetic shielding Precise geometrical alignment Fringe fields under control

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

Major challenge:
get systematic uncertainties
to the same level!

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Spin motion

Thomas-BMT equation:

magnetic moment

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

$$\left. + d\frac{m_0}{q\hbar S}\left(\vec{E} - \frac{\gamma}{(\gamma+1)}\vec{\beta}(\vec{\beta}\cdot\vec{B}) + c\vec{\beta}\times\vec{B}\right) \right\} \times \vec{S}$$

EDM

Ω: angular precession frequency $\qquad$ d: electric dipole moment

G: anomalous magnetic moment $\qquad$ γ: Lorentz factor

Storage rings: $\vec{B}$ vertical, $\vec{E}$ radial
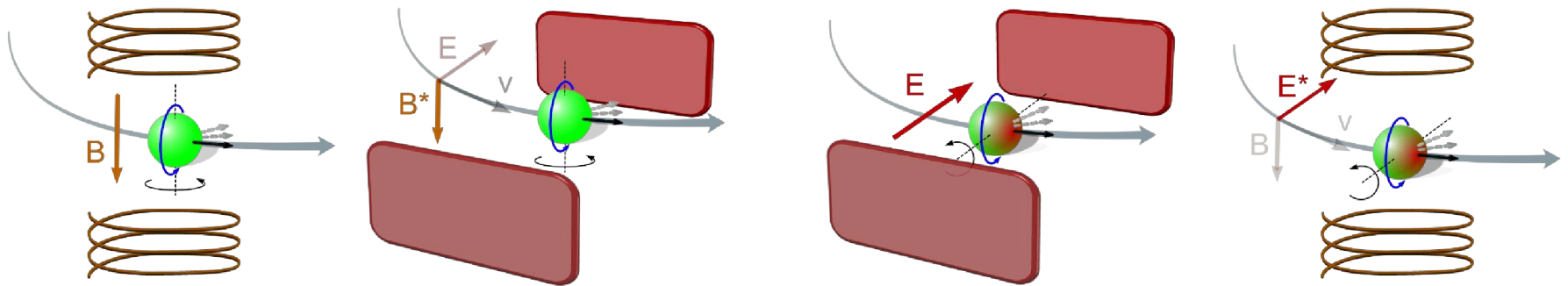
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Storage rings: general case

magnetic moment   EDM   Lorentz force

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

magnetic moment causes
fast spin precession: $\vec{s}_H \nparallel \vec{p}$

Ω: angular precession frequency
G: anomalous magnetic moment
d: electric dipole moment
γ: Lorentz factor

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Storage rings: electric ring

magnetic moment   EDM

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0}\left\{G\vec{B} + \underbrace{\left(\frac{1}{\gamma^2-1} - G\right)}_{\equiv 0!}\frac{\vec{\beta}\times\vec{E}}{c} + d\,\frac{m_0}{q\hbar S}\left(\vec{E} + c\vec{\beta}\times\vec{B}\right)\right\} \times \vec{S}$$

„frozen spin" : precession vanishes at magic momentum

$$G = \frac{1}{\gamma^2-1} \implies p = \frac{m}{\sqrt{G}}$$

only possible for $G > 0$

Dedicated ring for protons

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Storage rings: combined ring

magnetic moment   EDM

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

$$\equiv 0!$$

„frozen spin": proper combination of $\vec{B}$, $\vec{E}$ and γ
also for $G < 0$ (i.e. deuterons, ^{3}He)

All-in-one ring for protons, deuterons, ^{3}He

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Storage rings: magnetic ring

magnetic moment   EDM

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0}\left\{ G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G\right)\frac{\vec{\beta} \times \vec{E}}{c} + d\frac{m_0}{q\hbar S}\left(\vec{E} + c\vec{\beta} \times \vec{B}\right)\right\} \times \vec{S}$$
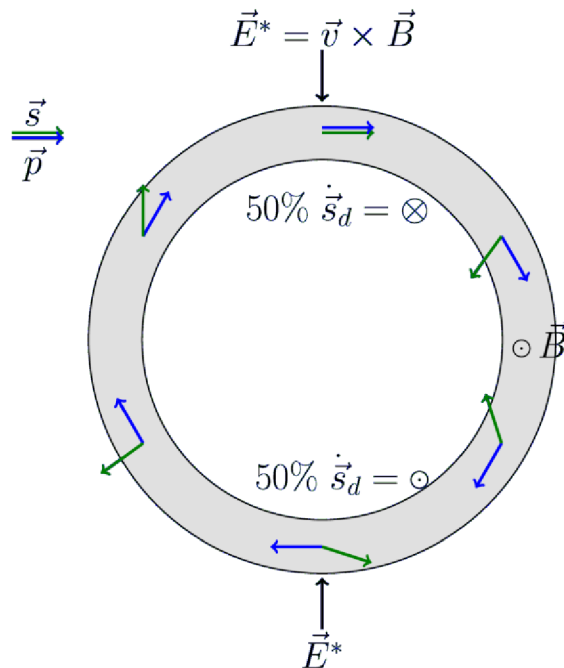
COSY: pure magnetic ring, polarized protons and deuterons

access to EDM via motional electric field $c\vec{\beta} \times \vec{B}$

Ideal starting place for R&D and a proof-of-principle experiment

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Pure magnetic ring

Due to fast precession longitudinal polarization component is

      50% of time parallel

      50% of time anti-parallel

to momentum

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

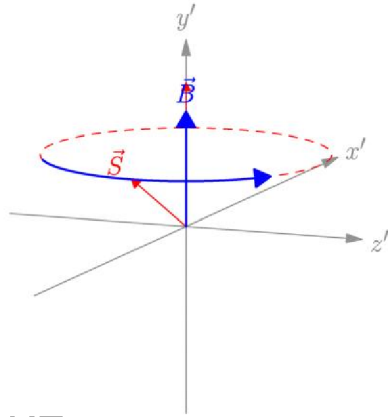E* field in the particle rest frame tilts spin due to EDM

      50% of time up and

      50% of time down

→ no net EDM effect

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Resonant rf Wien filter

Wien filter: Lorentz force vanishes → no effect on EDM rotation

Effect on horizontal precession:

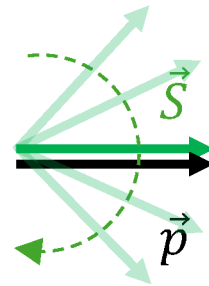|		
Without WF	50 %	50 %
Static WF	50 %	50 %

(precession just faster or slower)

Resonant rf WF	speed up prec.	slow down prec.
(resonant on precession frequency)	<50 %	>50%

net EDM effect

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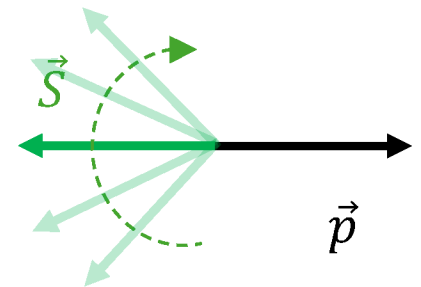
The RF Wien filter

Waveguide design:
provides $\vec{E} \times \vec{B}$ by design

Support for geodetics

Inner support tube

Support structure for electrodes

BPM (Rogowski coil)

Copper electrodes

Beam pipe (CF 100)

Ferrit cage

Belt drive for 90^0 rotation

Vacuum vessel with small angle rotator

Clamps for the Ferrit cage

~ 1 m

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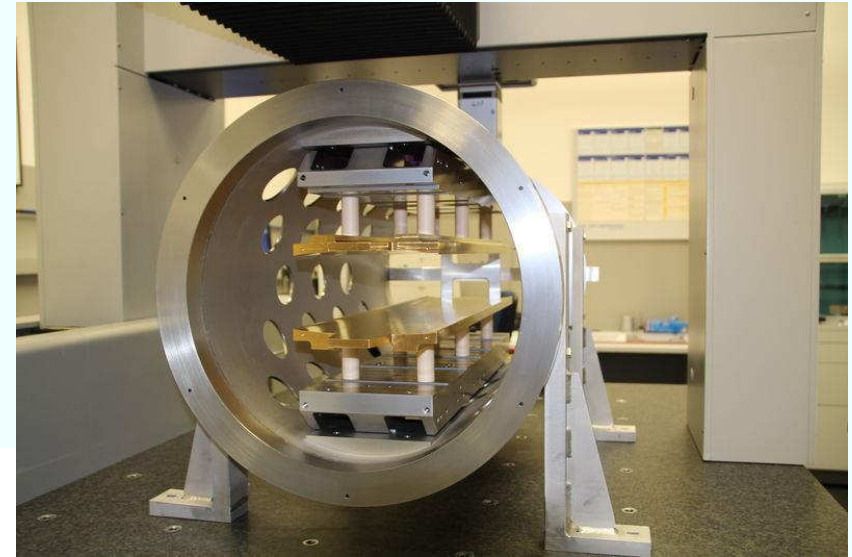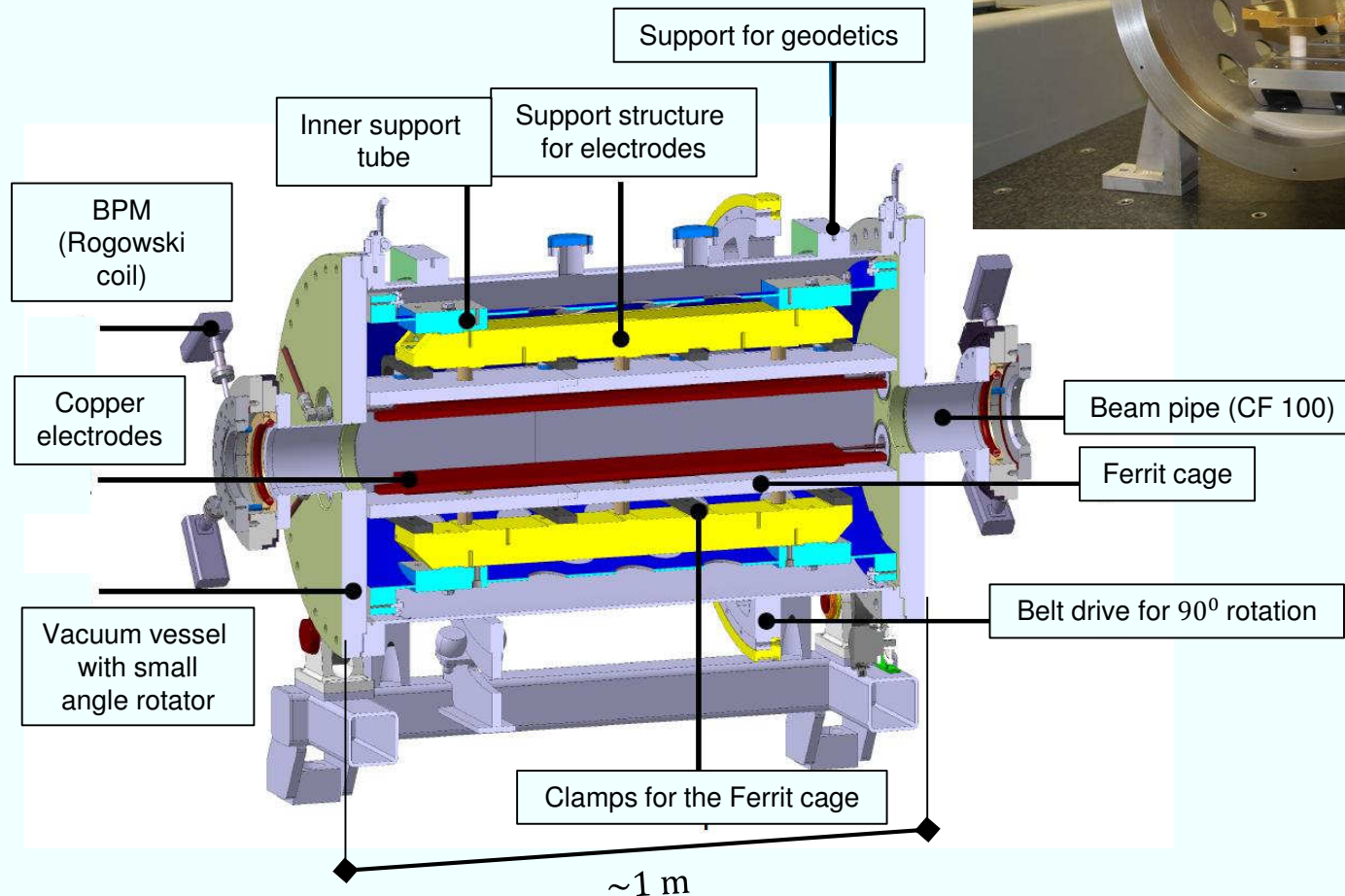
R&D at COSY

Thomas-BMT equation:

magnetic moment   neglect EDM

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

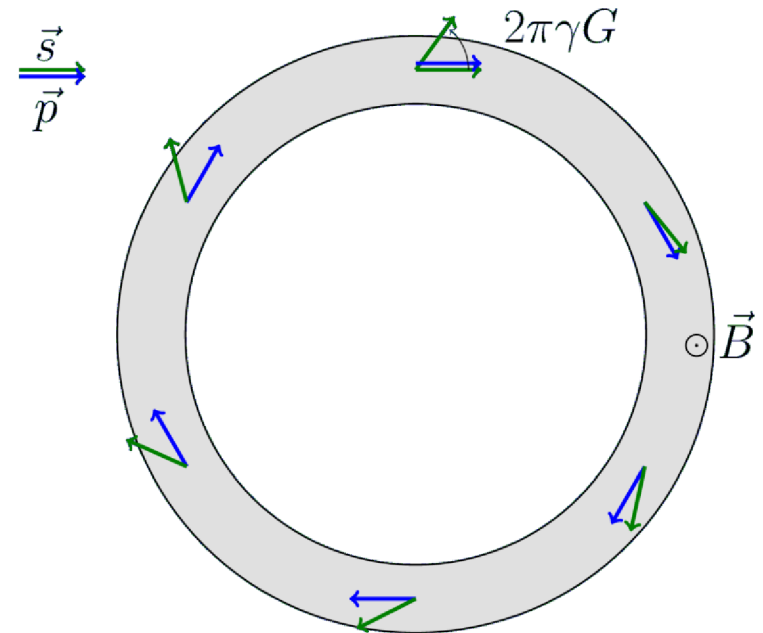spin tune $\nu_s = \dfrac{|\vec{\Omega}|}{|\vec{\omega}_{\text{cycl}}|} = \gamma G$

$\rightarrow$ phase advance per turn $2\pi\nu_s$

R&D with deuterons

p = 1 GeV/c
G = -0.14256177(72)
ν_s ≈ -0.161 → f ≈ 120 kHz

$2\pi\gamma G$

$\vec{s}$
$\vec{p}$

$\odot\,\vec{B}$

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(Some) Questions to be addressed

- Precise measurement of the precession frequency (spin tune)
  → also continuous and online

- Maximizing the spin coherence time (goal: ≈1000 s)

- Maintaining the spin direction
  → keep precession frequency stable
  → match frequency and phase to Wien filter radio frequency

- Study effects of field misalignments, orbit distortions, etc.

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Cooler Synchrotron COSY
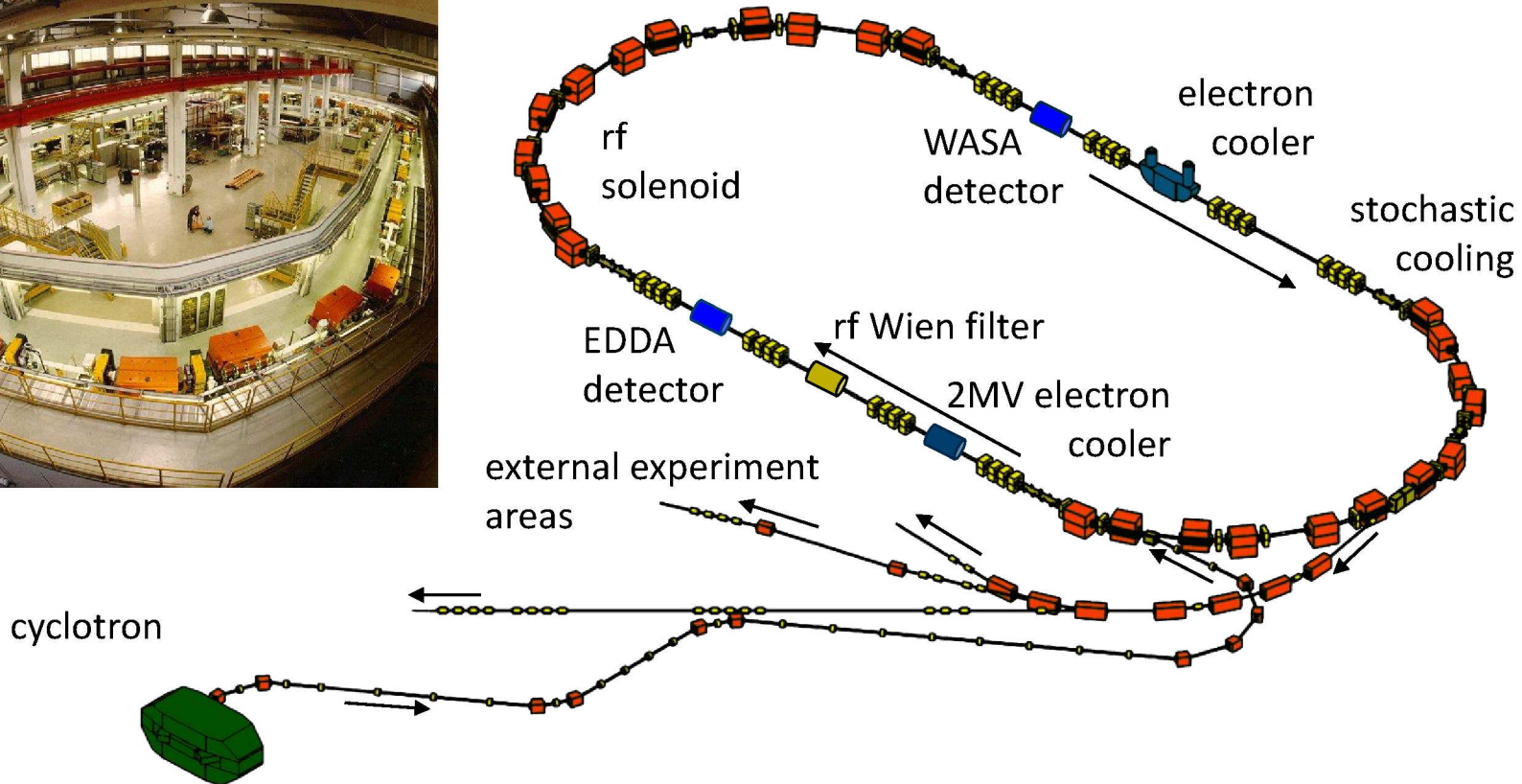
COSY provides cooled & polarized protons and deuterons with
p = 0.3 – 3.7 GeV/c

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Experimental setup

1. inject and accelerate vertically polarized deuterons to p = 1 GeV/c

2. bunch and (pre-)cool

3. turn spin by means of a RF solenoid into horizontal plane

4. extract beam slowly (within 100-1000 s) onto a carbon target, measure asymmetry and precisely determine spin precession

WASA detector

rf solenoid

EDDA detector

precession

$\vec{d}$
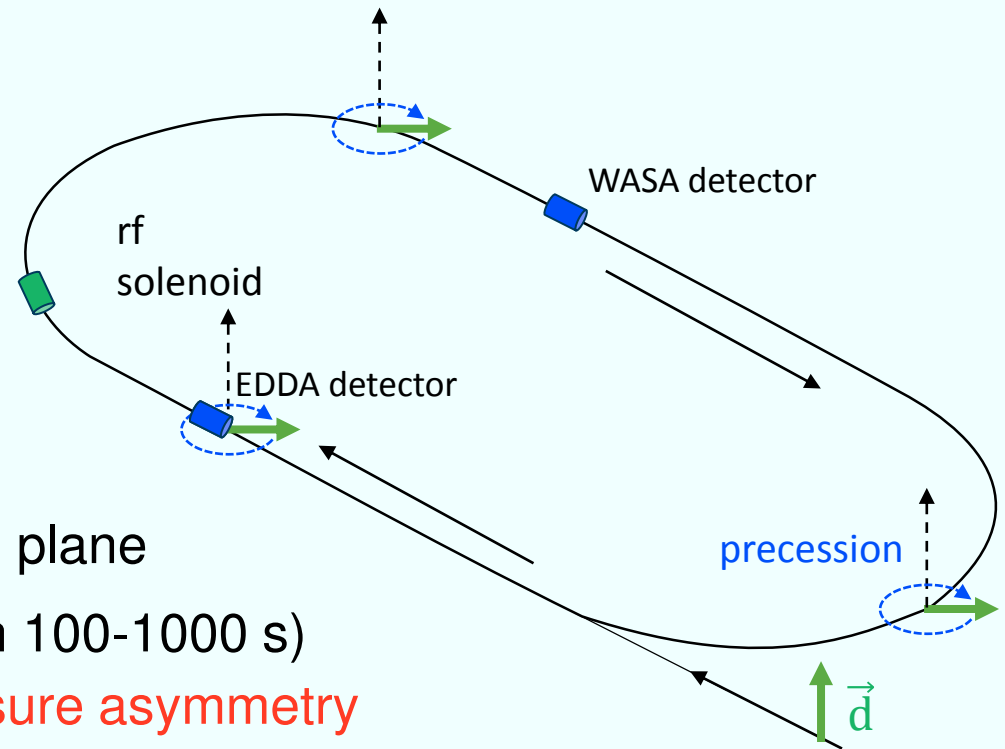
spin tune:

$$|\nu_s| = |\gamma G| = \frac{\text{spin precessions}}{\text{particle turn}} = \frac{f_{\text{prec}}}{f_{\text{rev}}} \approx \frac{120 \text{ kHz}}{750 \text{ kHz}} \approx 0.16$$

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Polarimetry

- elastic deuteron-carbon scattering

- spin-dependent cross section:

$$\sigma(\varphi) = \sigma_0 \left(1 + \frac{3}{2} P A \sin \varphi \right)$$

$$\sigma_+ = \sigma(90°) = \sigma_0 \left(1 + \frac{3}{2} P A \right)$$

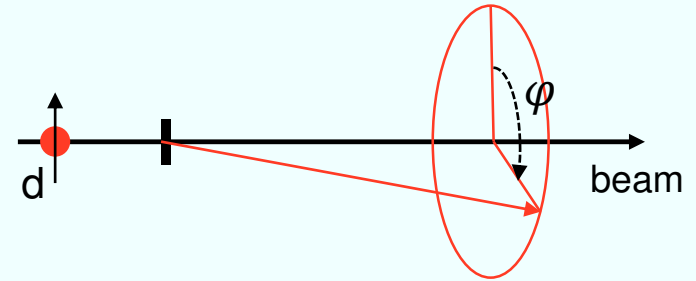$$\sigma_- = \sigma(-90°) = \sigma_0 \left(1 - \frac{3}{2} P A \right)$$

asymmetry:

$$\varepsilon = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{3}{2} P A$$
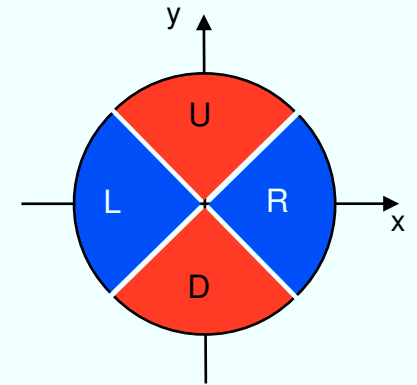
- segmented detector
  left – right asymmetry probes polarization along y
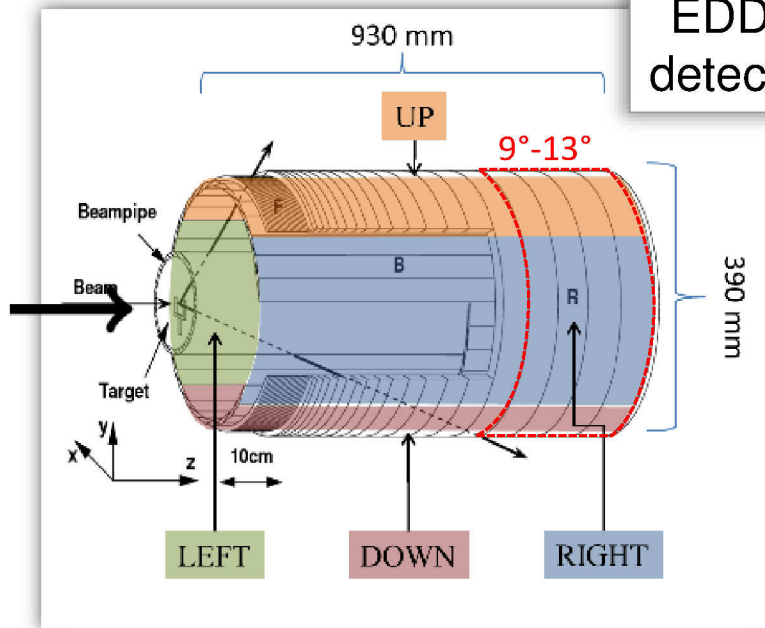 up – down asymmetry probes polarization along x
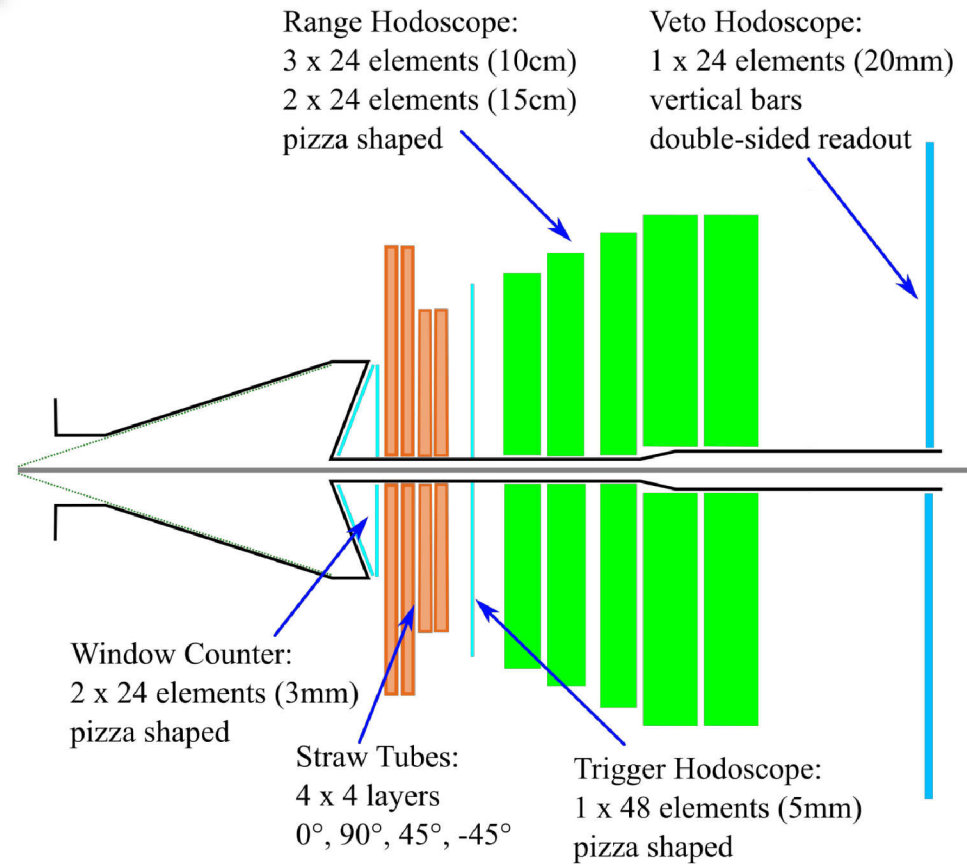
P: polarization
A: analyzing power

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Detector installations

EDDA
detector

930 mm

UP

9°-13°

390 mm

Beampipe

Beam

Target

10cm

LEFT   DOWN   RIGHT

WASA
detector

Range Hodoscope:
3 x 24 elements (10cm)
2 x 24 elements (15cm)
pizza shaped

Veto Hodoscope:
1 x 24 elements (20mm)
vertical bars
double-sided readout

Window Counter:
2 x 24 elements (3mm)
pizza shaped

Straw Tubes:
4 x 4 layers
0°, 90°, 45°, -45°

Trigger Hodoscope:
1 x 48 elements (5mm)
pizza shaped

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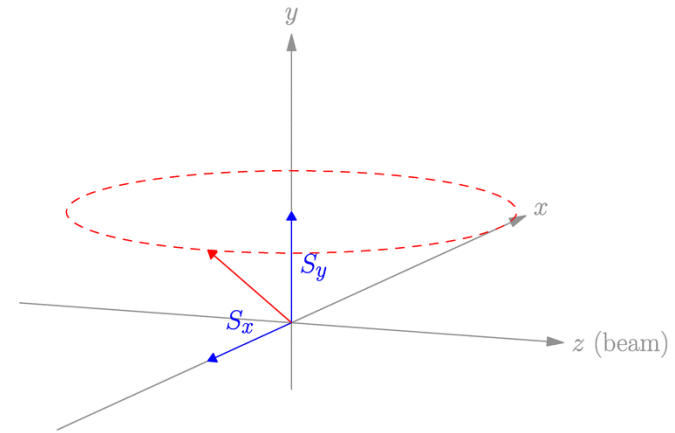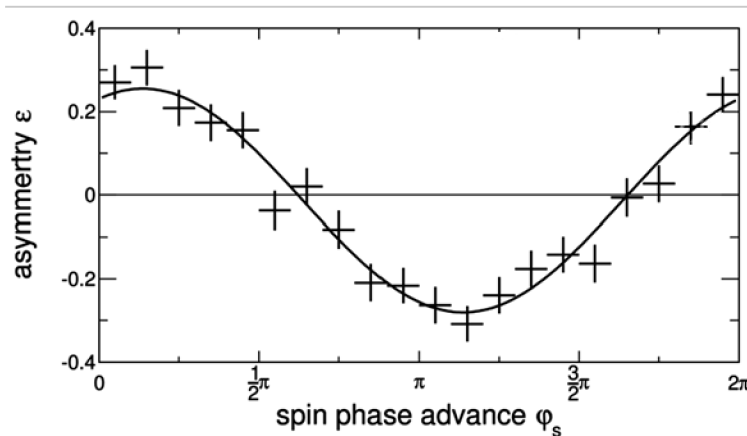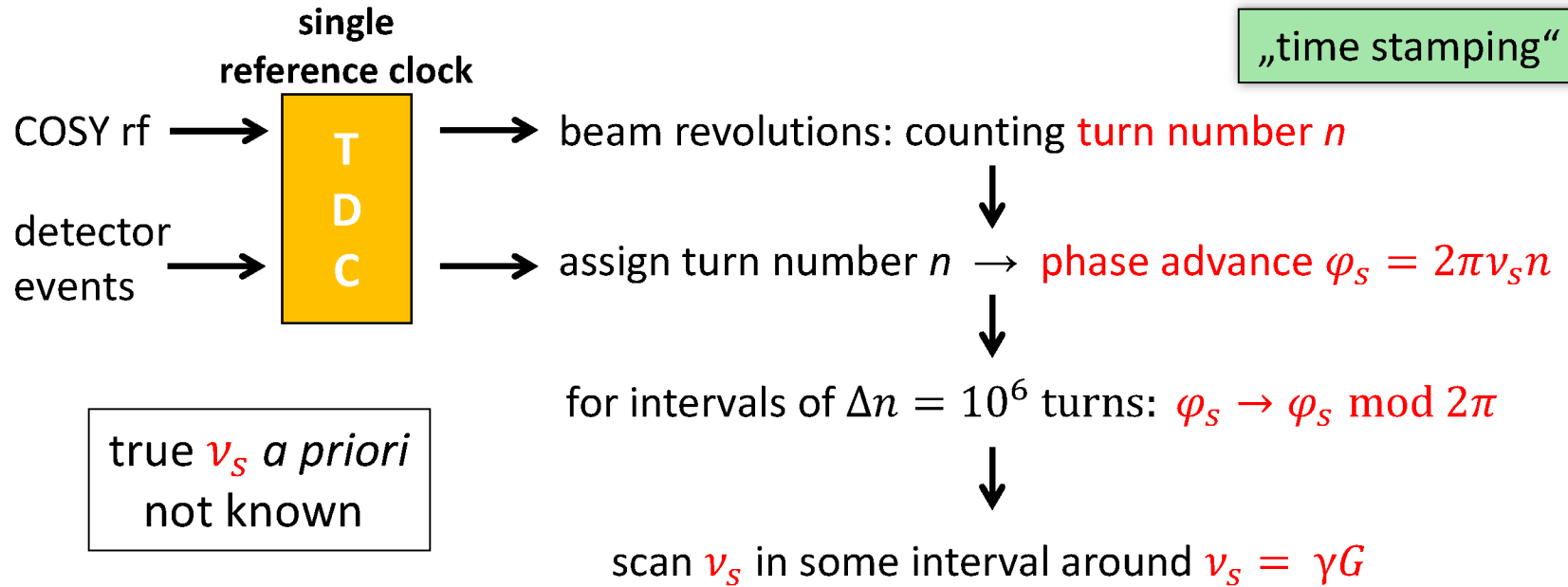
Spin precession

Time-dependent asymmetry

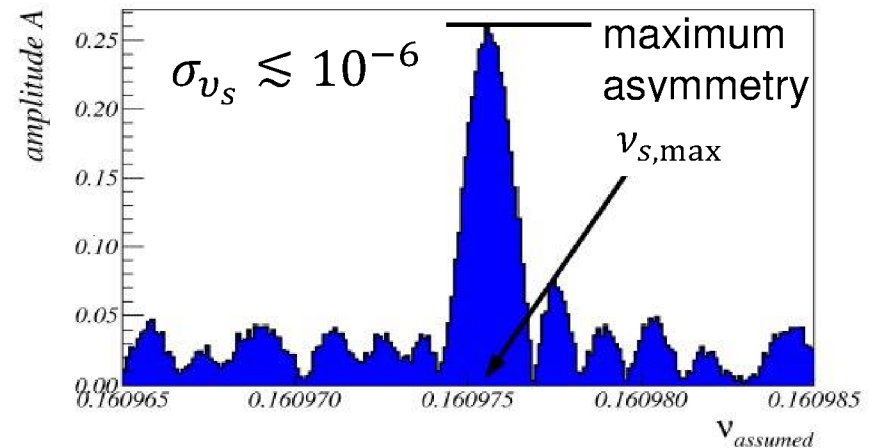$$\varepsilon_x = \frac{3}{2} PA \sin(2\pi v_s \cdot n_{\text{turns}})$$

Challenges

- precession frequency $f_{\text{prec}} \approx$ 120 kHz

- $v_s \approx$ -0.16   → 6 turns / precession

- event rate $\approx$ 5000 s^{-1} → 1 hit / 25 precessions

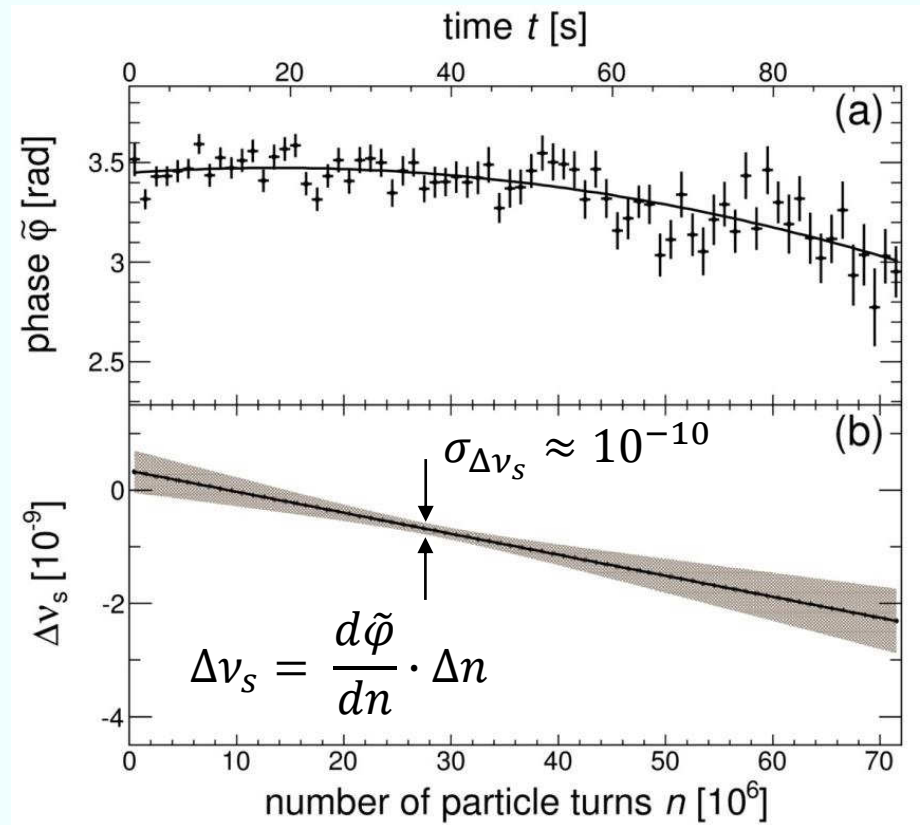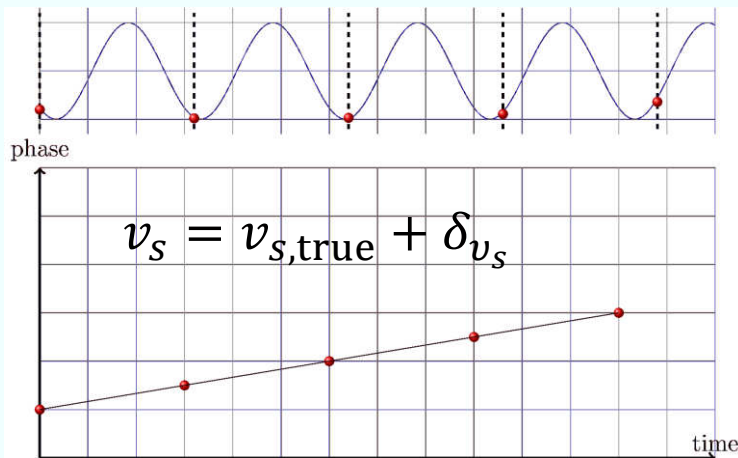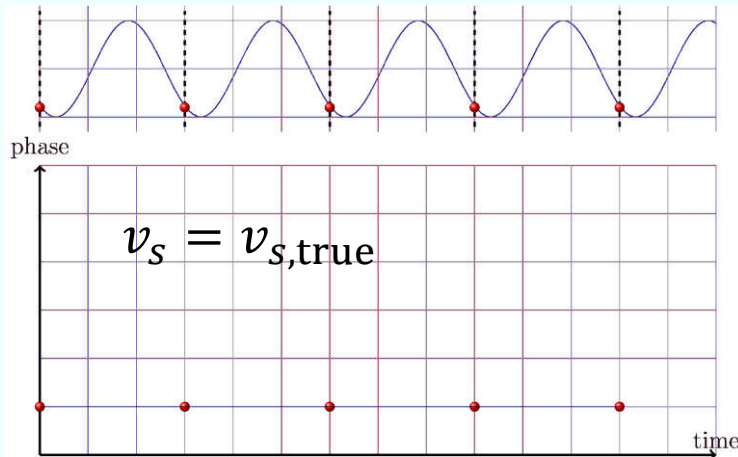   → no direct fit of the rates

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Unfolding the spin precession

single reference clock

COSY rf $\longrightarrow$ | T D C | $\longrightarrow$ beam revolutions: counting turn number n

detector events $\longrightarrow$

assign turn number $n \longrightarrow$ phase advance $\varphi_s = 2\pi\nu_s n$

for intervals of $\Delta n = 10^6$ turns: $\varphi_s \to \varphi_s \bmod 2\pi$

true ν_s *a priori* not known

scan ν_s in some interval around $\nu_s = \gamma G$

$\sigma_{\nu_s} \lesssim 10^{-6}$

maximum asymmetry

$\nu_{s,\max}$

see: Phys.Rev.Lett. 115, 094801 (2015)

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Precise determination of the spin tune

Monitoring phase of asymmetry (v_s fixed):

$$v_s = v_{s,\text{true}}$$

$$v_s = v_{s,\text{true}} + \delta_{v_s}$$

$$\sigma_{\Delta v_s} \approx 10^{-10}$$

$$\Delta v_s = \frac{d\tilde{\varphi}}{dn} \cdot \Delta n$$

see: Phys.Rev.Lett. 115, 094801 (2015)

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Spin tune: probing field imperfections
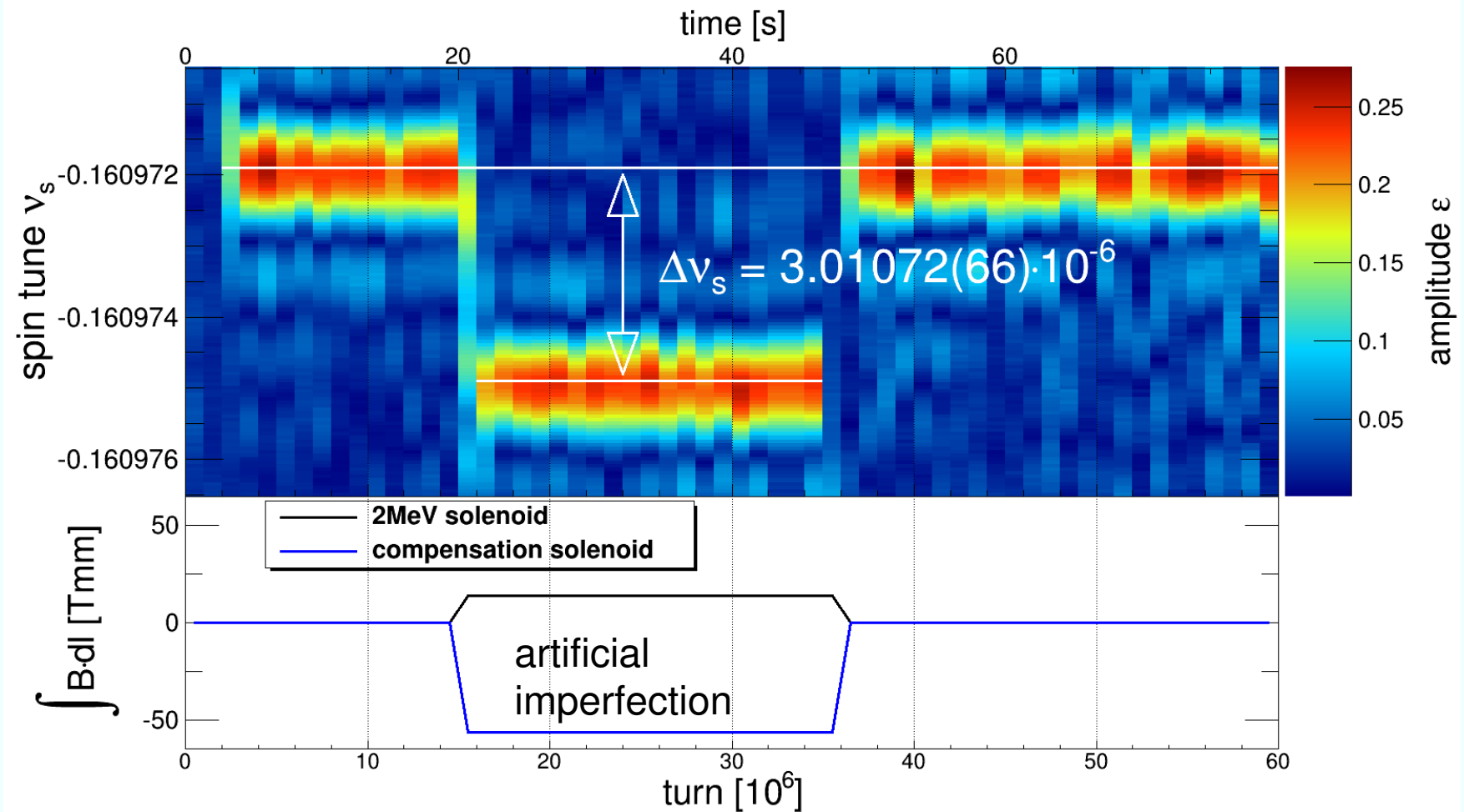
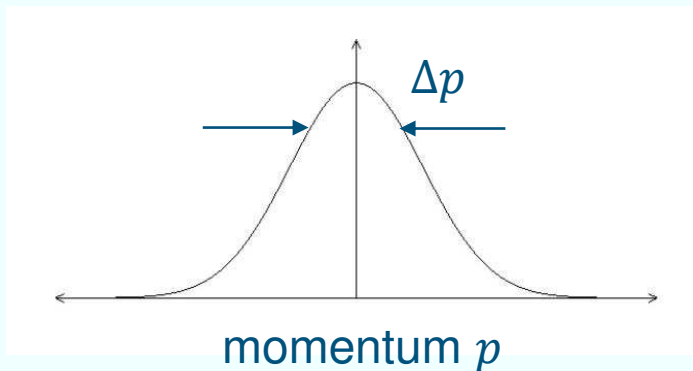# Spin Coherence Time (SCT)

Ensemble of ≈ 10^9 deuterons: coherent precession needed!

Ideal case

- all particles have exactly the same momentum — no
- all particles travel the same path (orbit) in the ring — no
- all particles see the same fields — no

Example

momentum p

$$\frac{\Delta\gamma}{\gamma} = \beta^2 \frac{\Delta p}{p} \approx 10^{-4} = \frac{\Delta\nu}{\nu}$$

0.2 10^{-3}
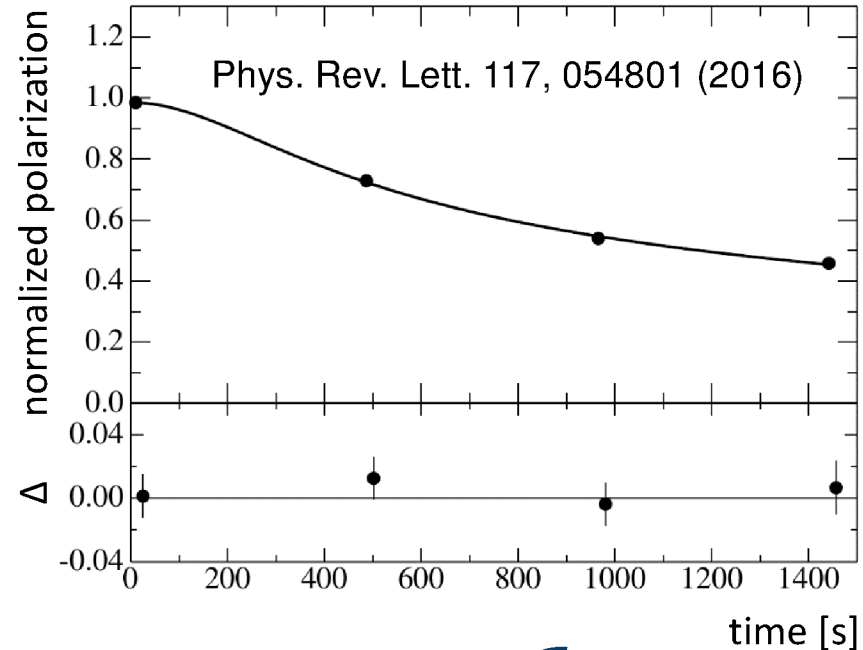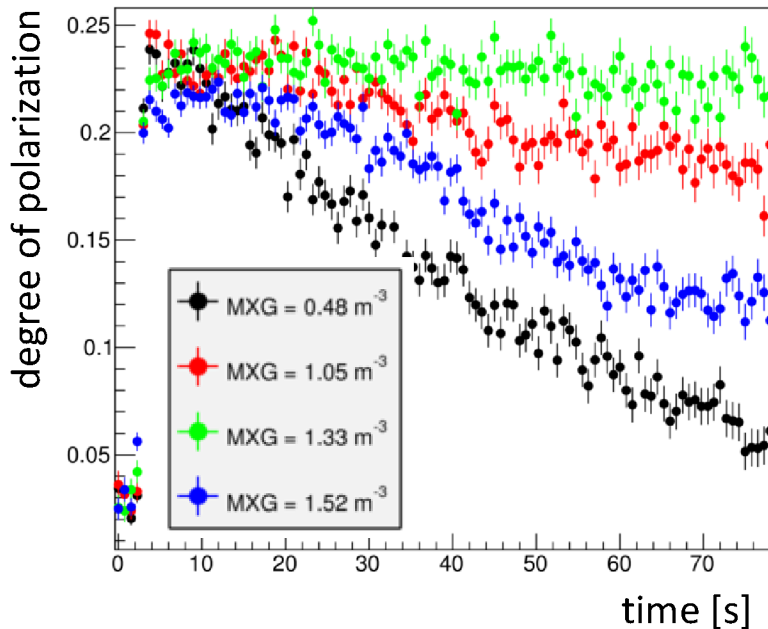
$$\Delta\nu \approx 10^{-4} \cdot 0.16 \approx 10^{-5}$$

revolution frequency

$$\Delta\varphi = 2\pi \cdot 10^{-5} \cdot 10^6 \text{s}^{-1} \approx 60 \, {}^{\text{rad}}/_{\text{s}}$$

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Spin Coherence Time (SCT)

- unbunched beam: $\frac{\Delta\gamma}{\gamma} \approx 10^{-5} \implies$ decoherence in < 1s

- bunching: eliminate effects on $\frac{\Delta p}{p}$ in 1st order $\to \tau \approx 20\ s$

- correcting higher order effects using sextupoles

  and (pre-) cooling $\to \tau \approx 1000\ s$

Phys. Rev. Lett. 117, 054801 (2016)

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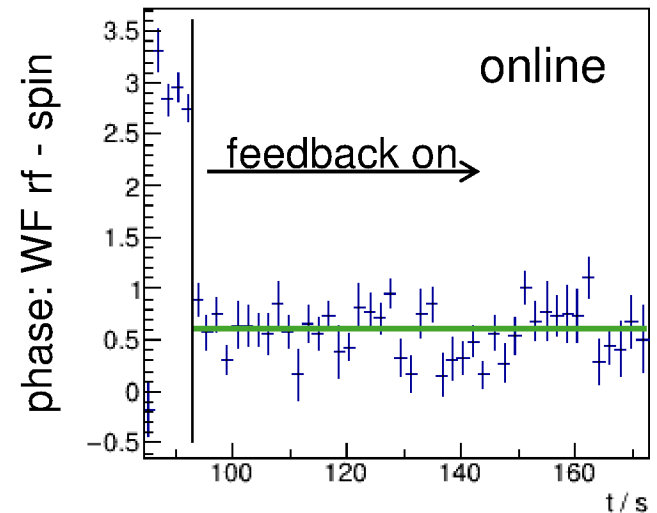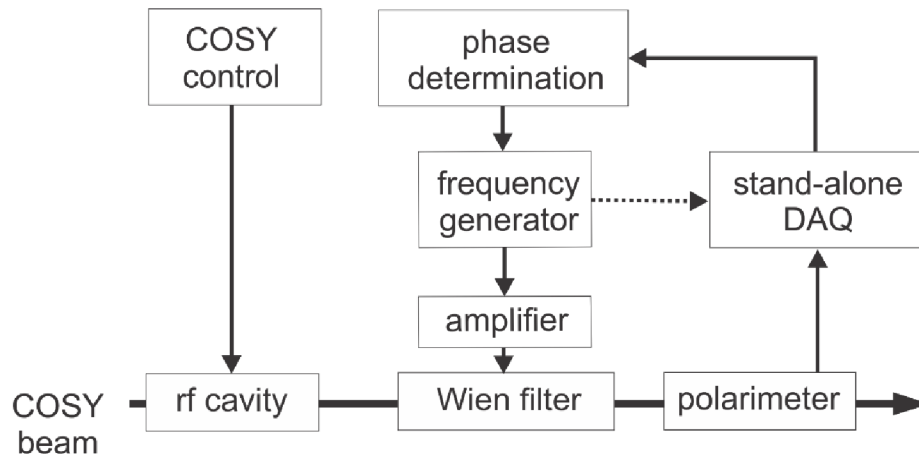# Spin tune: feedback system (phase lock)

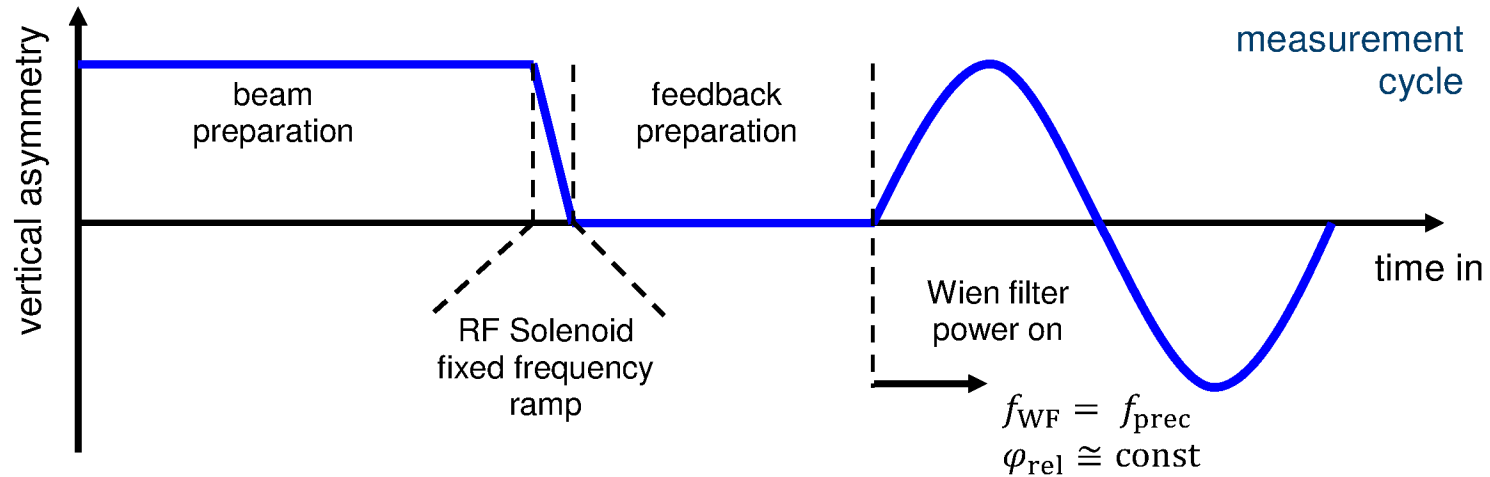## Challenges:

- maintain resonance frequency and phase between spin precession and Wien filter

- maintain frozen spin condition in a future dedicated ring

Implementation at COSY:
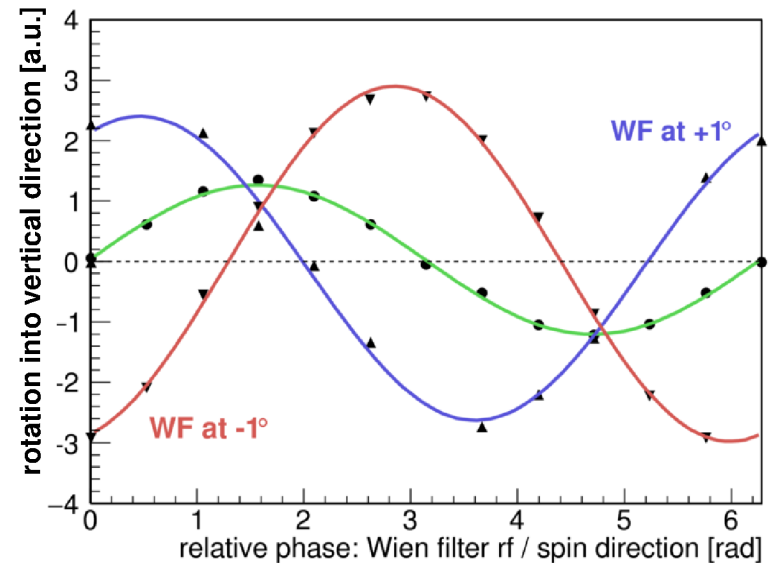
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Measurements with the Wien filter

Build-up of vertical component caused by
- EDM effect
- field and alignment errors in the ring

Systematic study by controlled changes of the device alignments and fields

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Summary

- EDMs sensitive to new sources of CP violation

- Mechanism for CP violation: EDMs of charged hadrons needed

- Observable: spin precession in electric fields in storage rings

- COSY: ideal starting point for R&D and a pre-cursor experiment

Outlook

- pre-cursor experiment at COSY:
  first measurement with lower sensitivity on the way

- dedicated storage ring:
  different options are currently under investigation

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