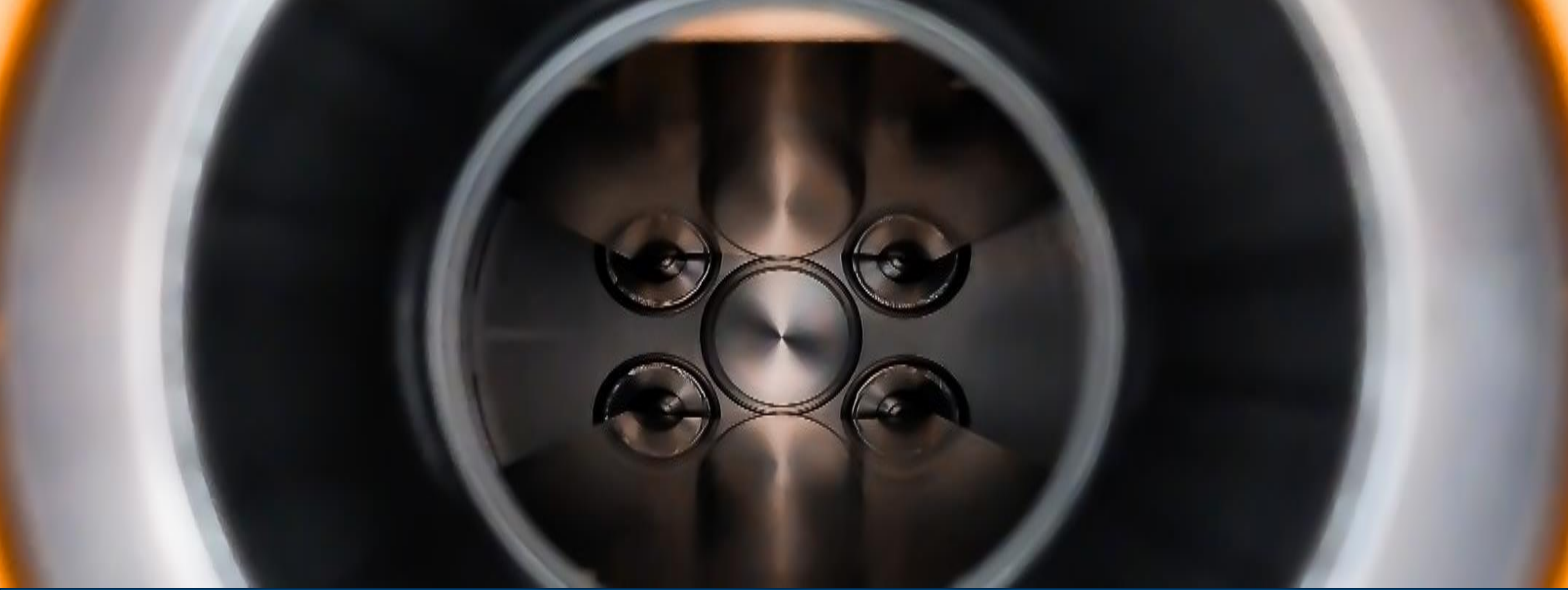

MEASUREMENT OF ELECTRIC DIPOLE MOMENTS AT STORAGE RINGS

VOLKER HEJNY, INSTITUT FÜR KERNPHYSIK
FORSCHUNGSZENTRUM JÜLICH

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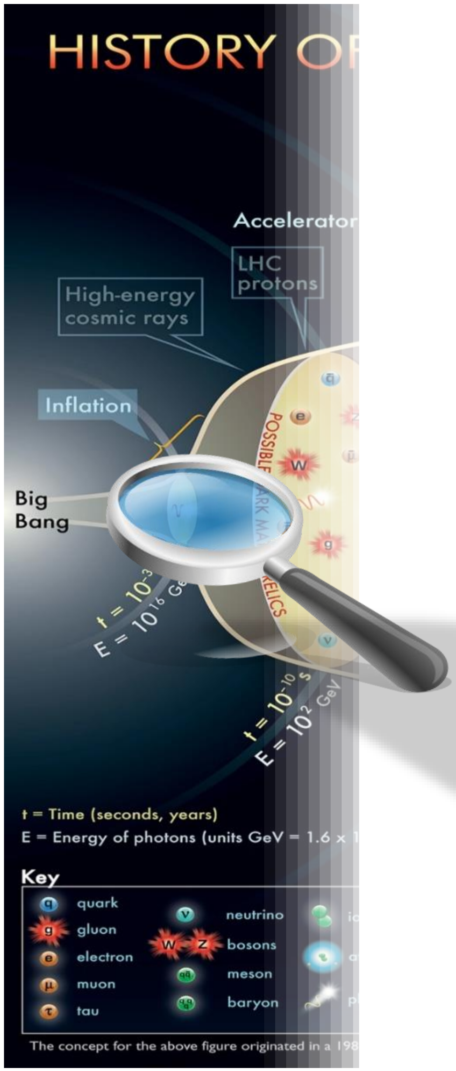
Why are we here?



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

$\frac{\text{matter - antimatter}}{\text{radiation}}$

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

Outline

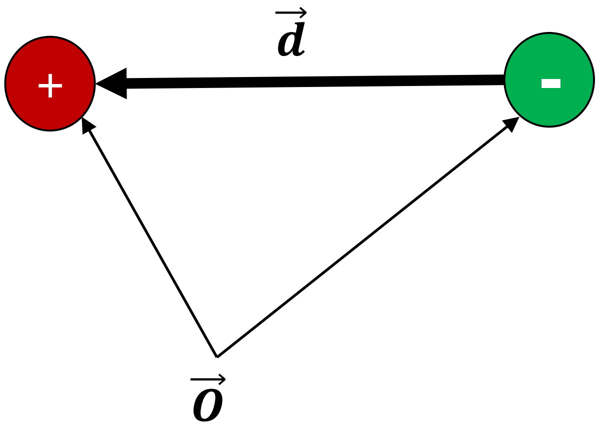
- Electric Dipole Moments
  - What are those?
  - How can they help?
- EDM measurements using storage rings
  - Basic principles
  - Options
- R&D and first measurements at COSY

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

Electric Dipole Moments (EDM)

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

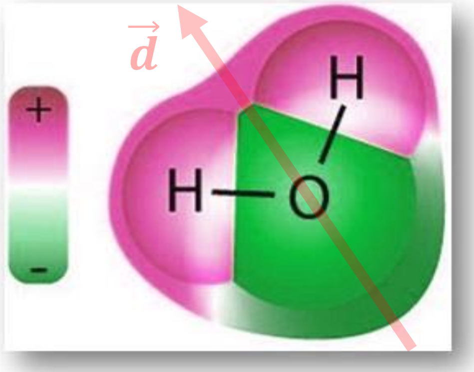
charge x distance



Example: water molecule

charge separation

electric dipole moment
$d \approx 4 \times 10^{-9}$ *e* cm

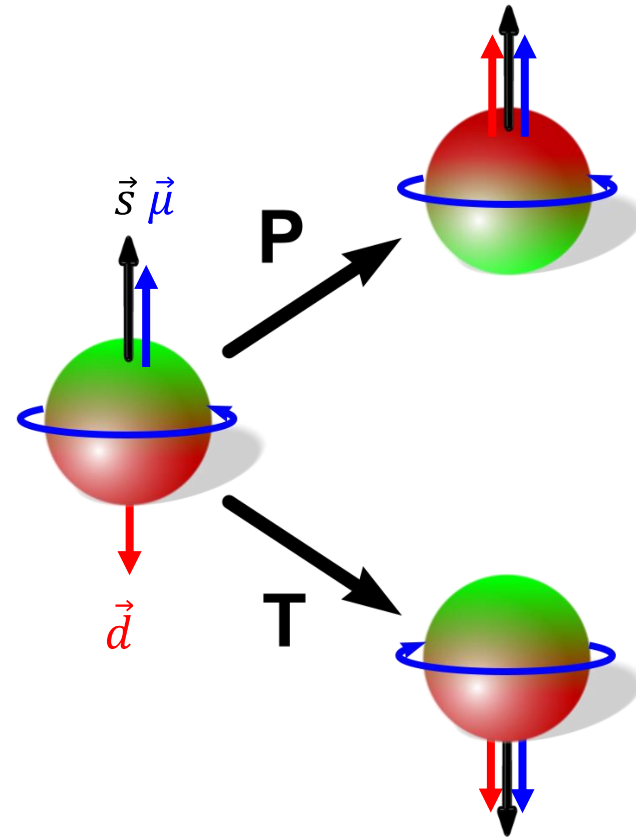


EDMs of elementary particles

$\vec{s}$ spin

$\vec{d}$ electric dipole moment

$\vec{\mu}$ magnetic moment



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

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

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

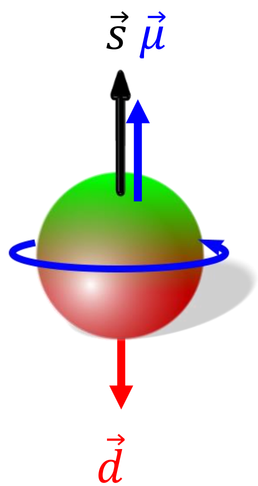
$\mathcal{T}$: $$H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$

EDM measurements test violation of fundamental symmetries $\mathcal{P}$, $\mathcal{T}$ and $\mathcal{CP}$ (via $\mathcal{CPT}$)

So what is the difference?

elementary particle

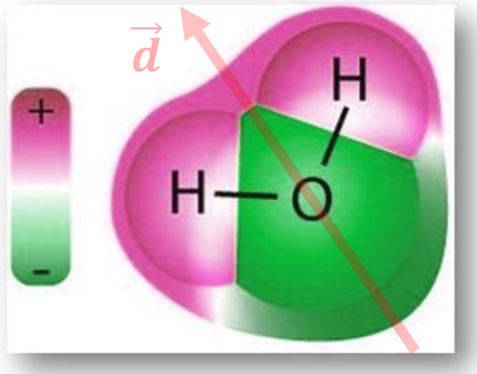
EDM violates $\mathcal{P}$, $\mathcal{T}$



defined parity!

water molecule

EDM allowed



degenerated
ground state
with mixed parity!

How can that help?

Reminder: excess of matter in the universe

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

Sakharov (1967): $\mathcal{CP}$ violation needed for baryogenesis

⇩

New sources of $\mathcal{CP}$ violation needed
to explain this mismatch

⇩

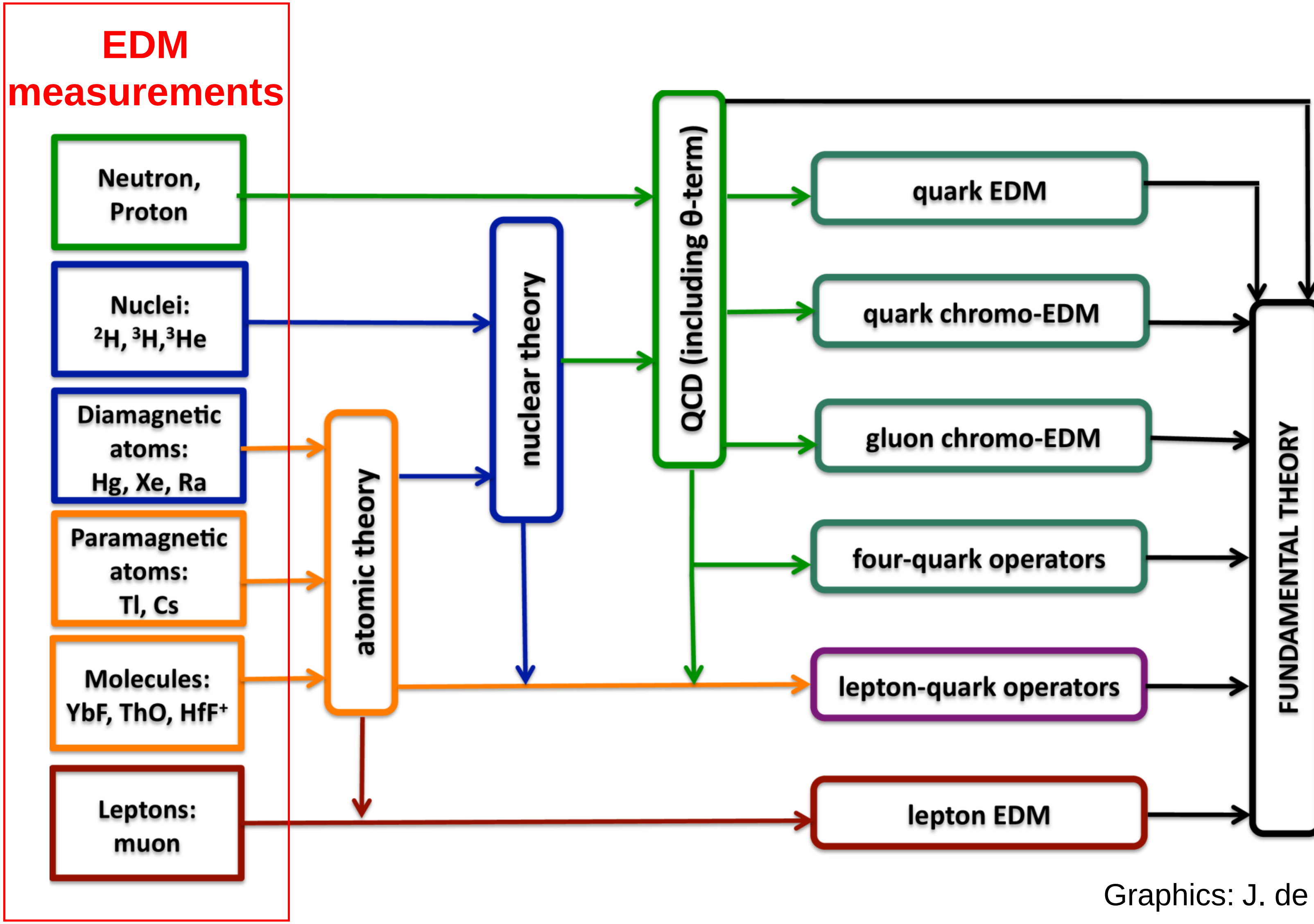
EDMs as a probe for $\mathcal{CP}$ violation beyond the SM

Sources of $\mathcal{CP}$ 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

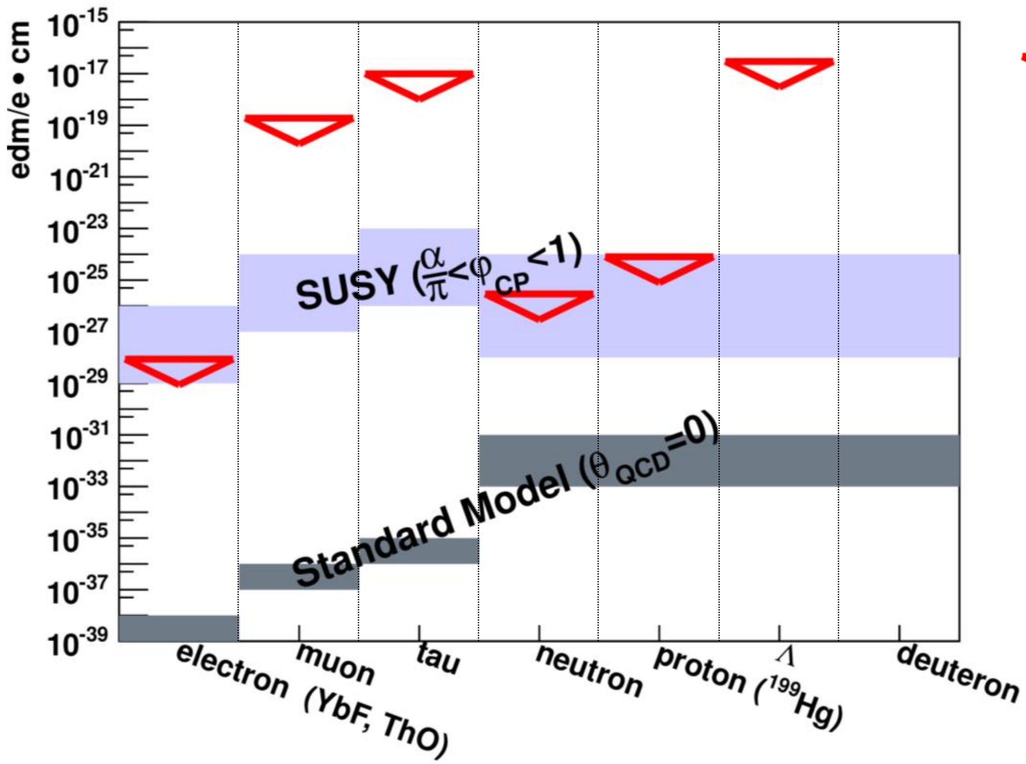
Different sources of $\mathcal{CP}$ violation result in a different EDM for different particle types

Disentangling $\mathcal{CP}$ violation …



Graphics: J. de Vries

Current EDM limits



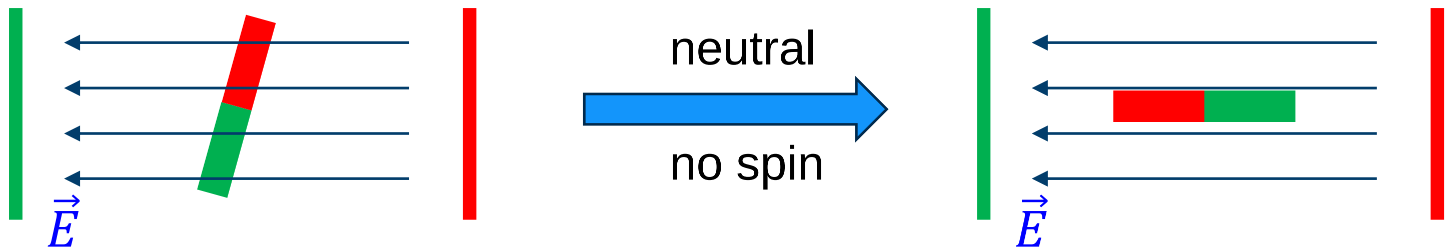
- proton
  no direct measurement
- deuteron
  no measurement

Here: EDMs of charged particles

How to measure EDMs?

Common strategy for all EDM measurements:

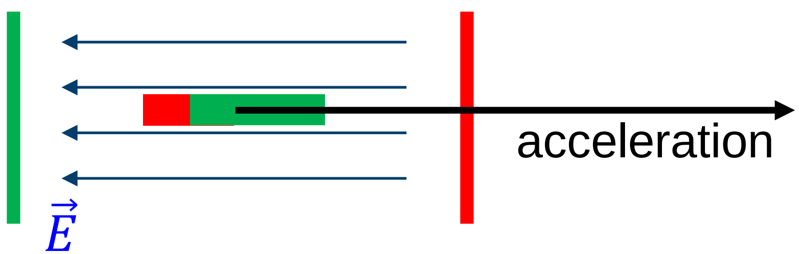
$\longrightarrow$ measure interaction of $\vec{d}$ with electric field $\vec{E}$

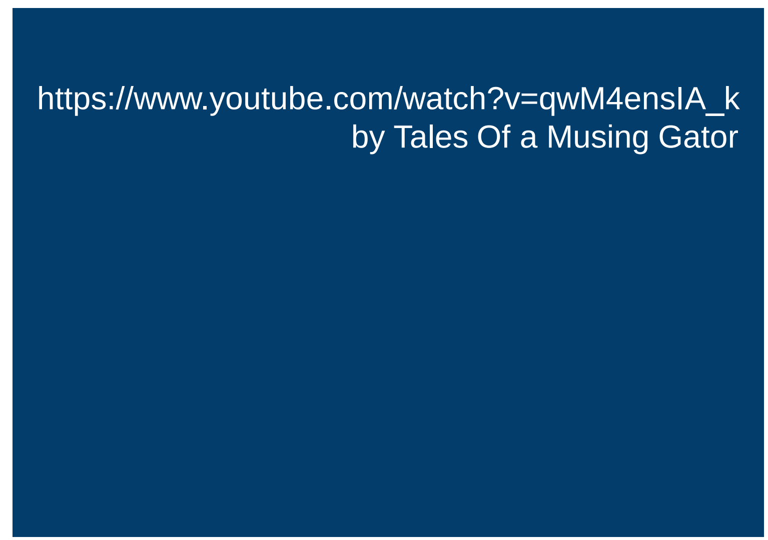


With spin:

$\longrightarrow$ precession

For charged particles:





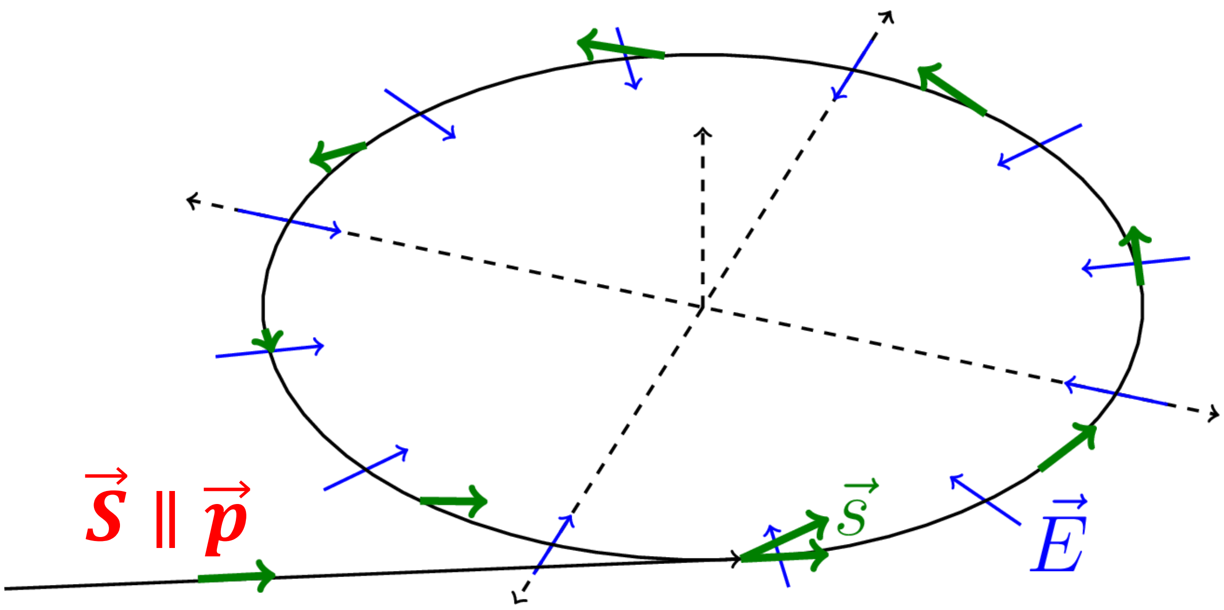
How to measure EDMs of charged particles?

Electric field accelerates particles

→ use a storage ring

Ideal case:

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



Build-up of vertical polarisation by slow precession $s_\perp \propto |d|$

"Ad-hoc" boundary conditions

Very slow spin precession	Long measurement times (*t* ≈ 1000 s) High electric fields (*E* ≈ 10 MV/m) High degree of polarization (*P* ≈ 0.8) Precise polarisation measurement (analysing power *A* ≈ 0.6, acc. *f* ≈ 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

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

Major challenge:
get systematic uncertainties
to the same level!

Spin motion

Thomas-BMT equation:

magnetic moment

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

EDM

Ω: angular precession frequency

G: anomalous magnetic moment

d: electric dipole moment

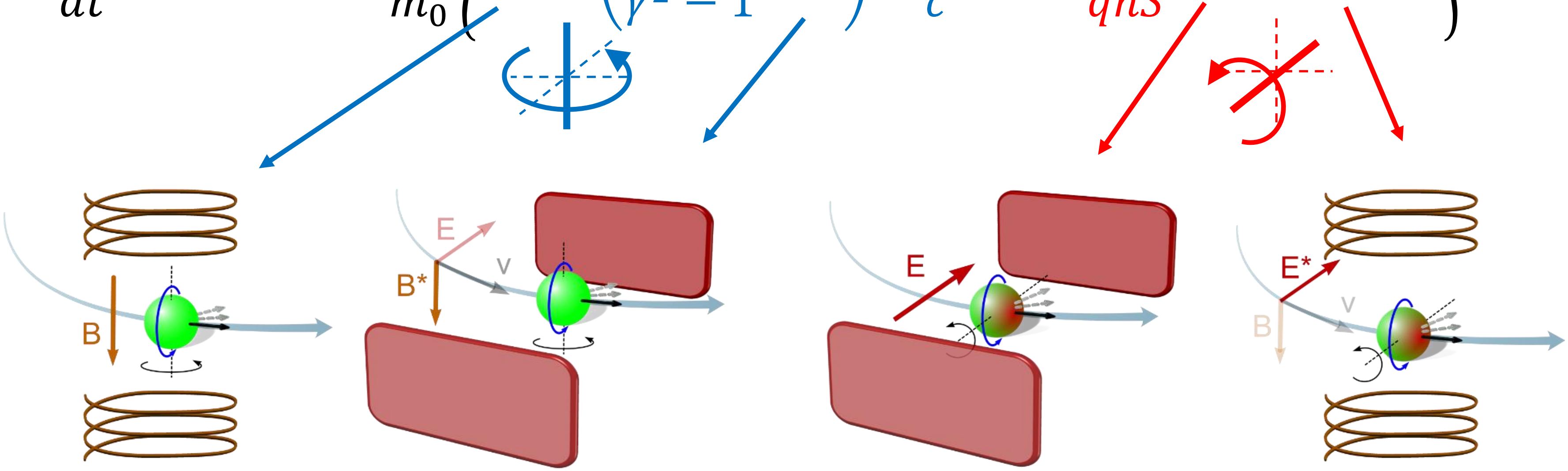
γ: Lorentz factor

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

Storage rings: general case

magnetic moment EDM

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



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

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

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

only possible for $G > 0$

Dedicated ring for protons

Storage rings: combined ring

magnetic moment EDM

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

„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

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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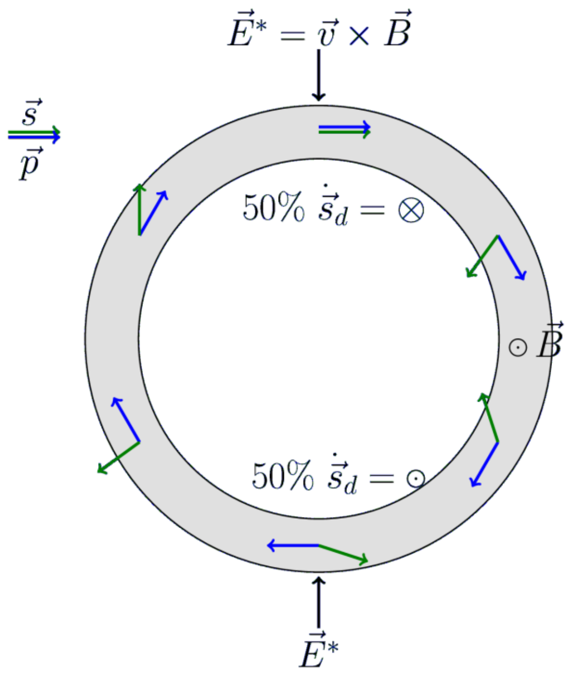
Pure magnetic ring

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

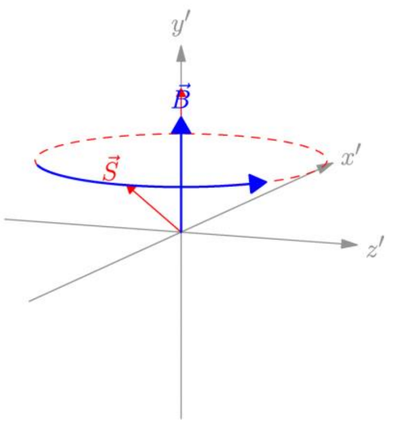
50% of time down

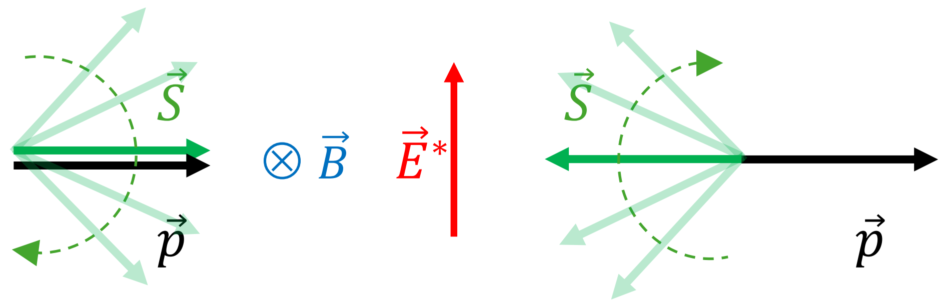
→ no net EDM effect

Resonant rf Wien filter

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

Effect on horizontal precession:



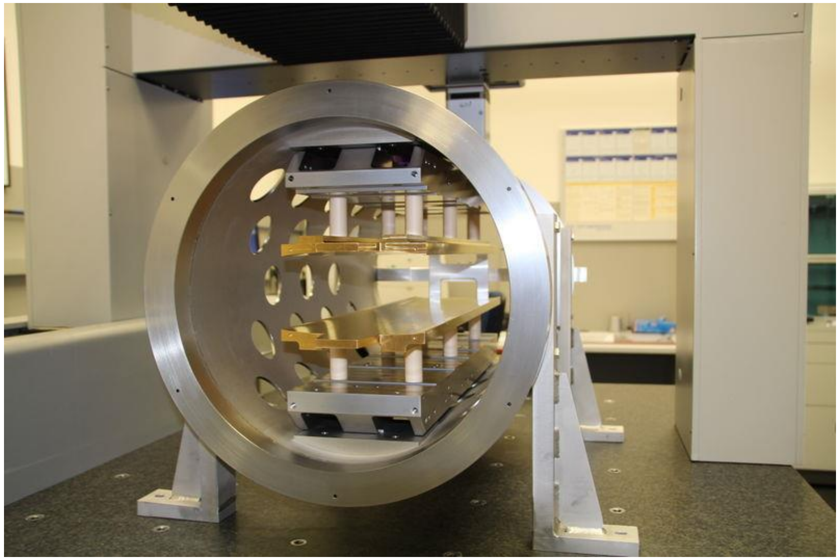


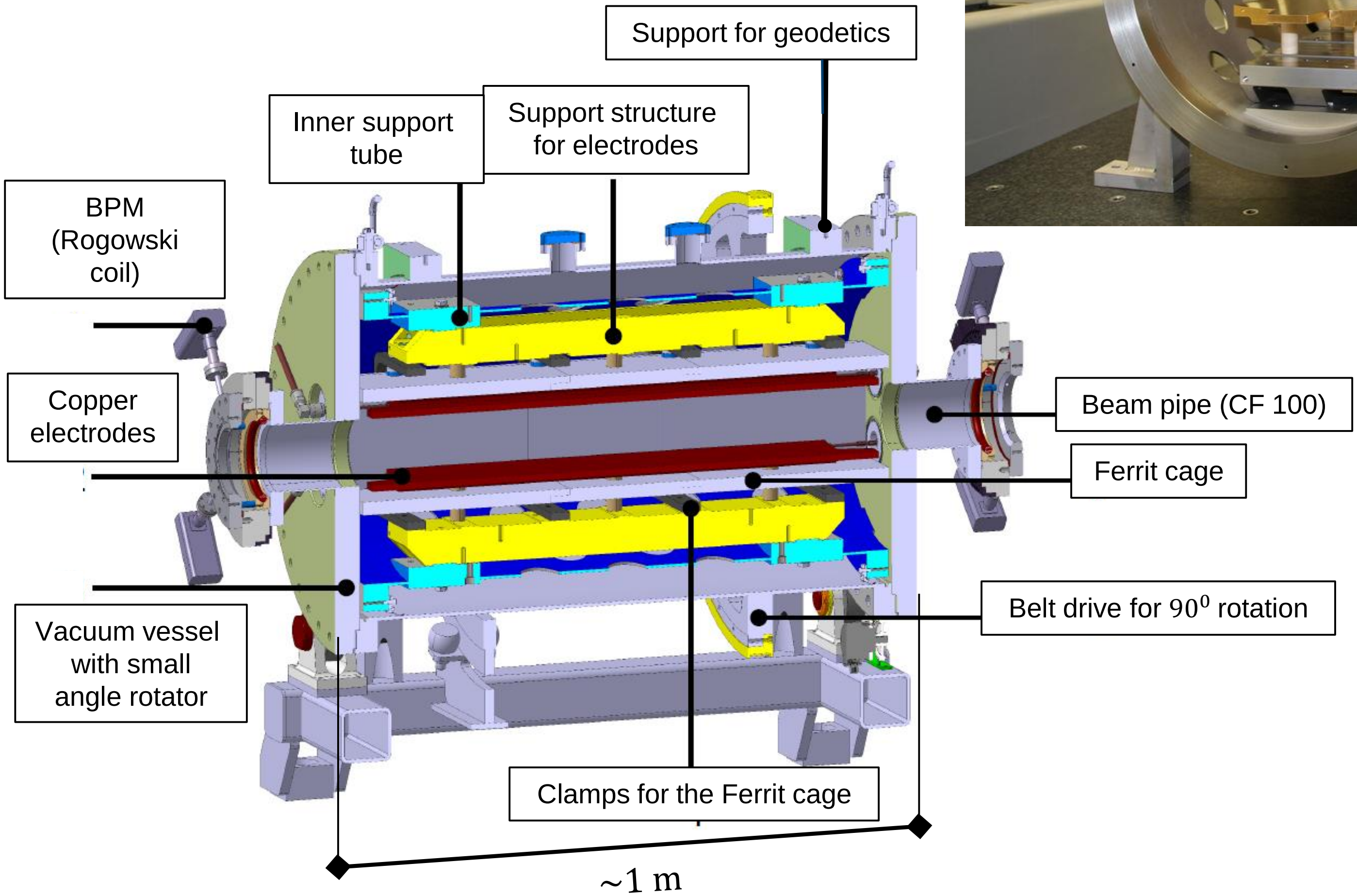
Without WF	50 %	50 %
Static WF	50 %	50 %
(precession just faster or slower)		
Resonant rf WF	speed up prec.	slow down prec.
(resonant on precession frequency)	<50 %	>50%

net EDM effect

The RF Wien filter

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





R&D at COSY

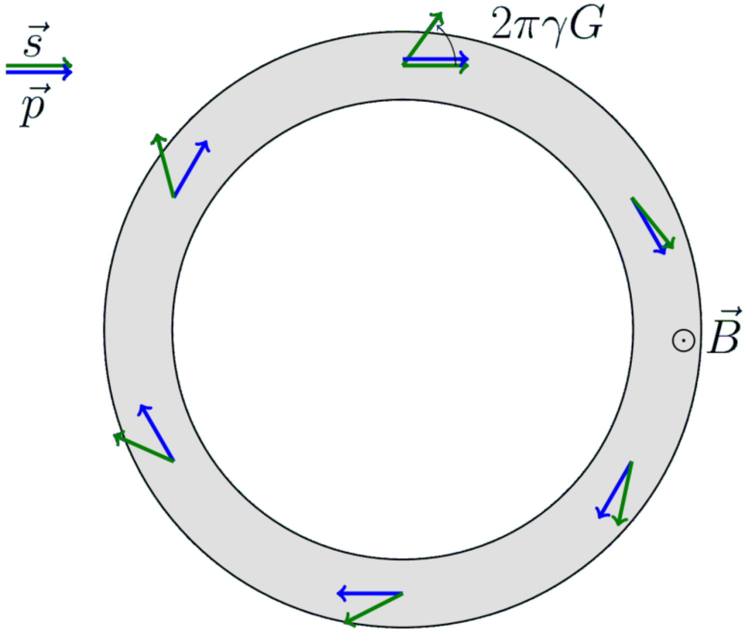
Thomas-BMT equation:

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

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



R&D with deuterons

p = 1 GeV/c

G = -0.14256177(72)

ν_s ≈ -0.161 $\longrightarrow$ *f* ≈ 120 kHz

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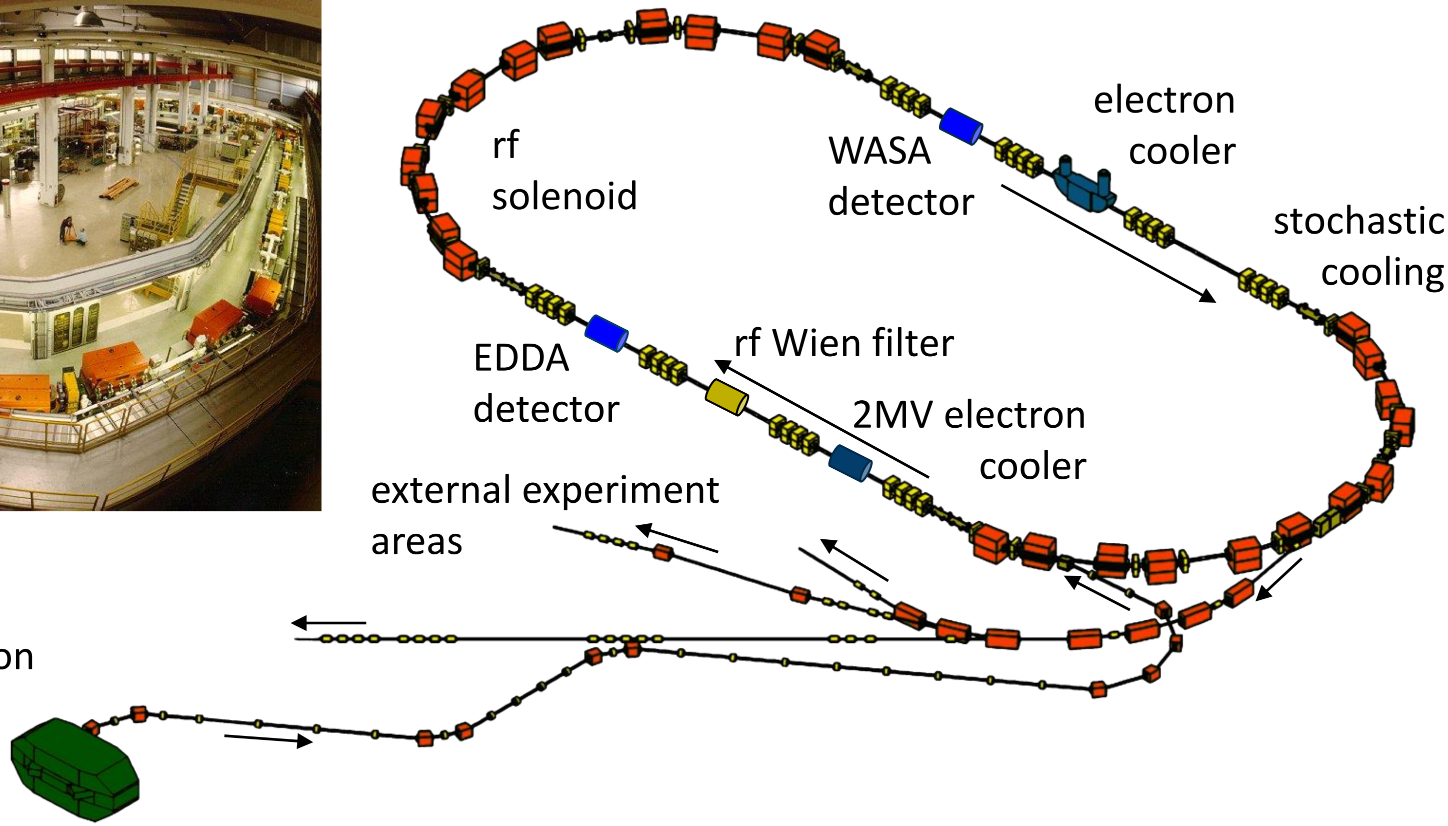
(Some) Questions to be addressed

- Precise measurement of the precession frequency (spin tune)
  $\longrightarrow$ also continuous and online
- Maximizing the spin coherence time (goal: ≈1000 s)
- Maintaining the spin direction
  $\longrightarrow$ keep precession frequency stable
  $\longrightarrow$ match frequency and phase to Wien filter radio frequency
- Study effects of field misalignments, orbit distortions, etc.

Cooler Synchrotron COSY



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

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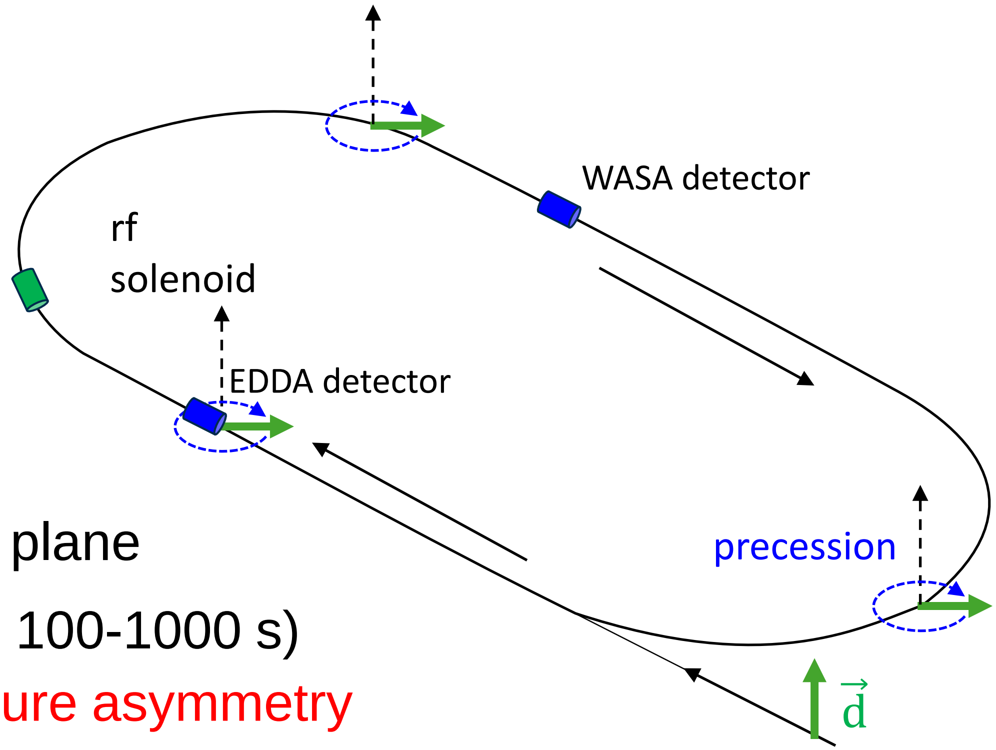
Experimental setup



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

spin tune:

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

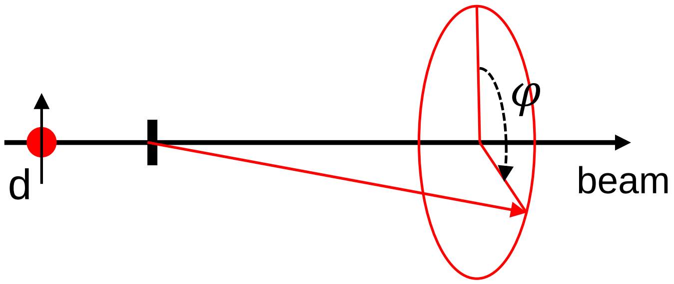
Polarimetry

- elastic deuteron-carbon scattering
- spin-dependent cross section:

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

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

$$\sigma_- \quad = \sigma(-90°) \; = \sigma_0 \left(1 - \frac{3}{2} PA\right)$$

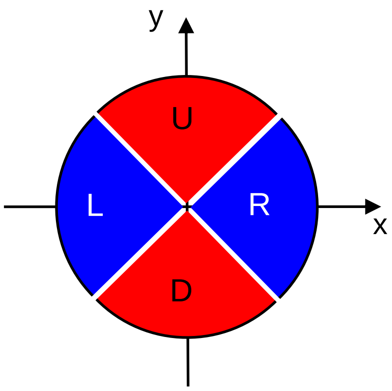


P: polarization
A: analyzing power

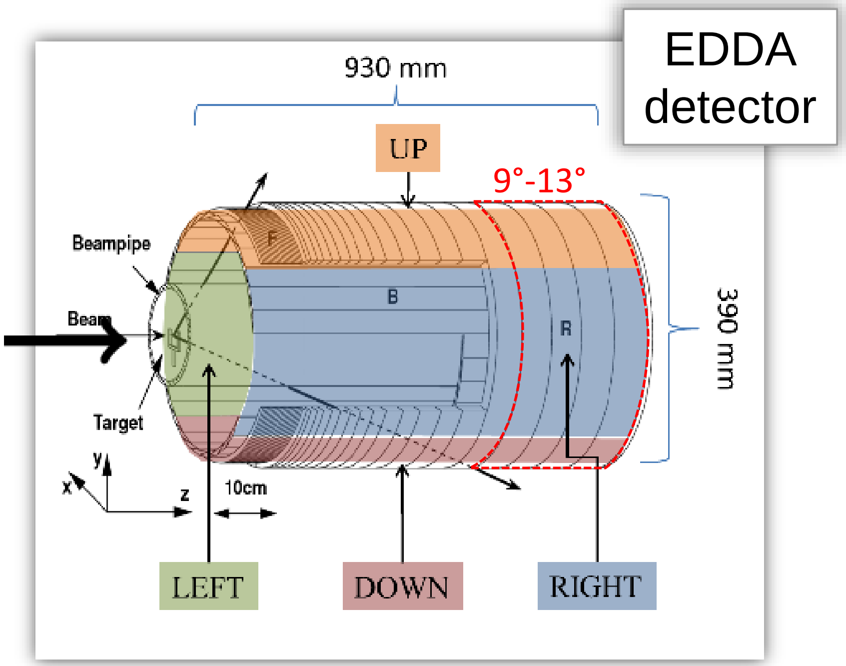
asymmetry:

$$\varepsilon \quad = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{3}{2} PA$$

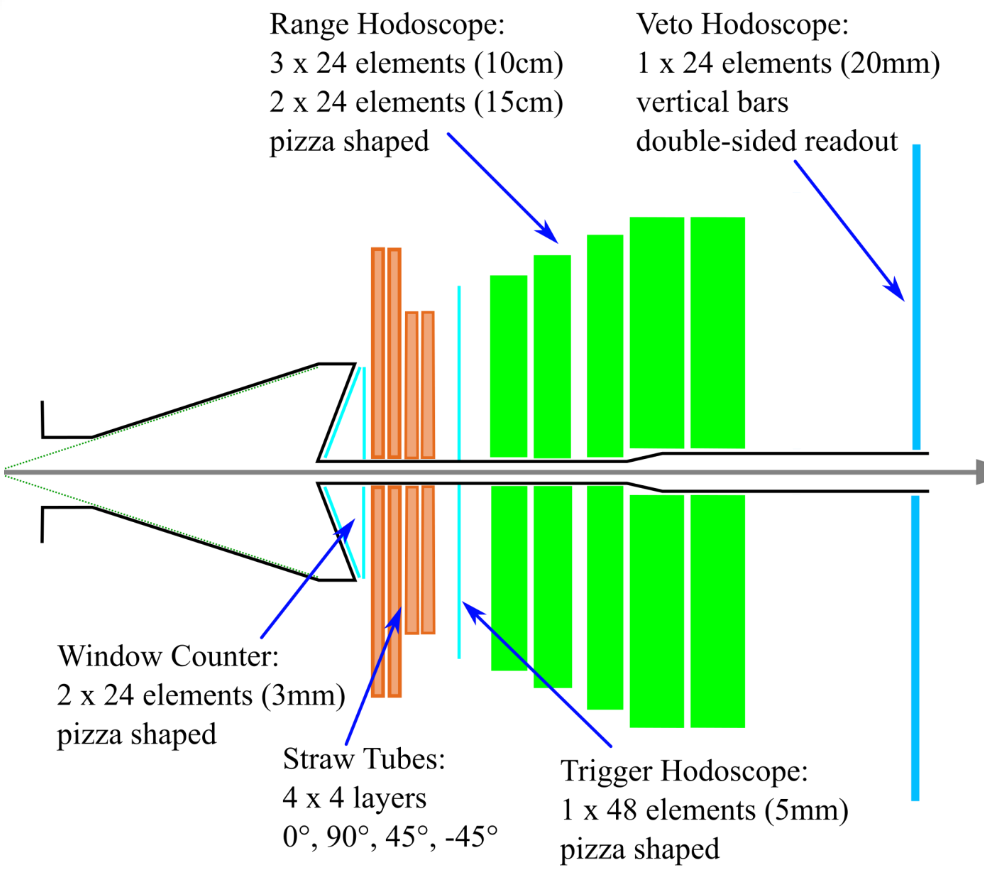
- segmented detector
left – right asymmetry probes polarization along y
up – down asymmetry probes polarization along x



Detector installations



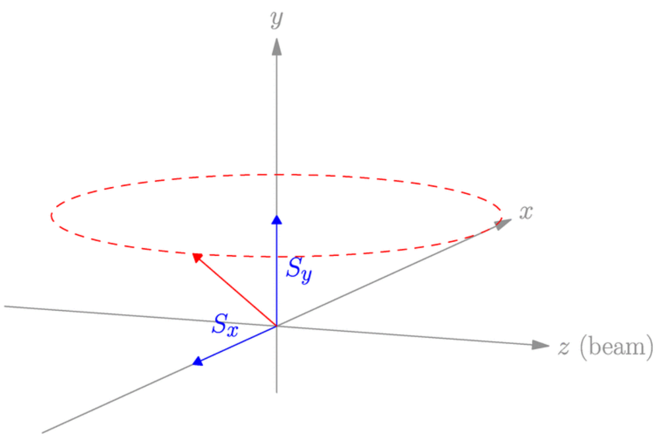
WASA
detector



Spin precession

Time-dependent asymmetry

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



Challenges

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

→ no direct fit of the rates

Unfolding the spin precession

„time stamping“

single reference clock

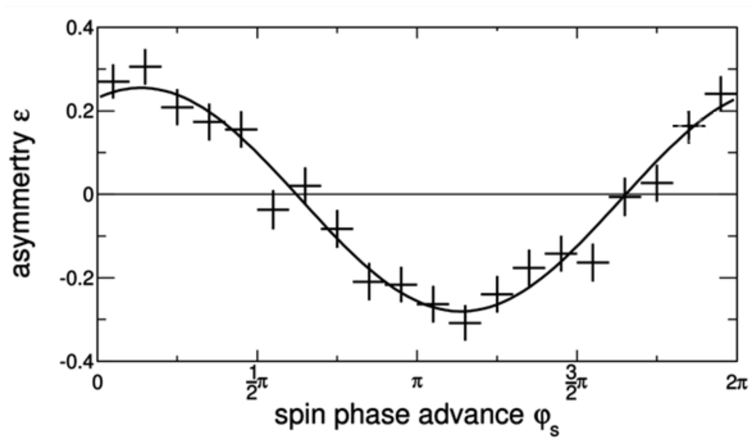
COSY rf → **TDC** → beam revolutions: counting turn number n

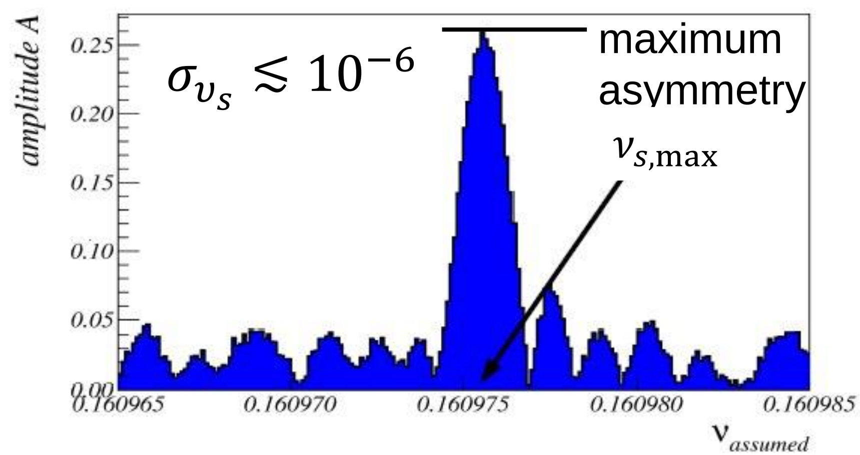
detector events → **TDC** → assign turn number n $\rightarrow$ phase advance $\varphi_s = 2\pi\nu_s n$

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

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

true ν_s *a priori* not known

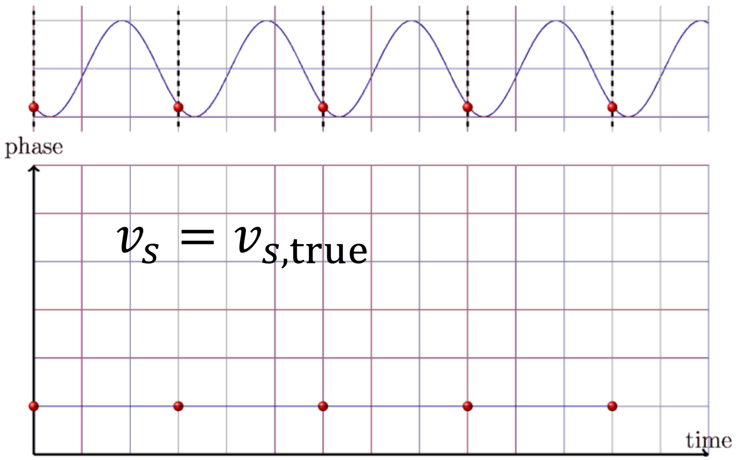


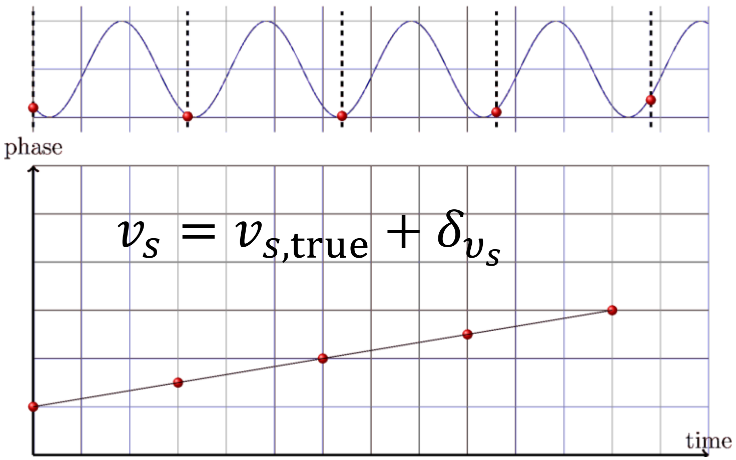


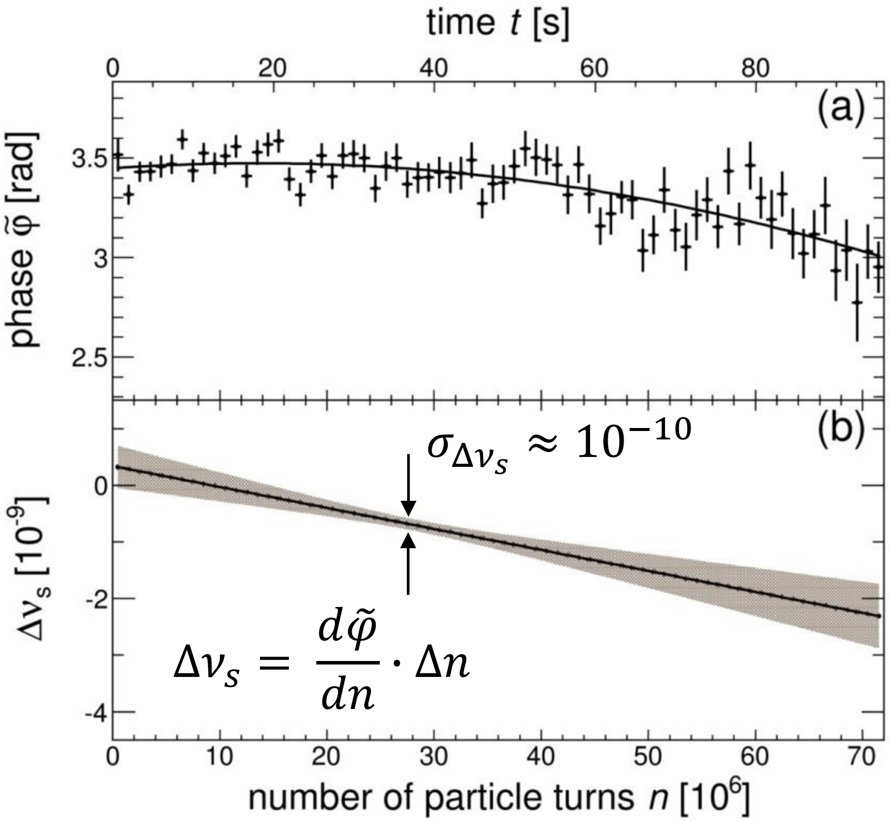
see: Phys.Rev.Lett. 115, 094801 (2015)

Precise determination of the spin tune

Monitoring phase of asymmetry (ν_s fixed):

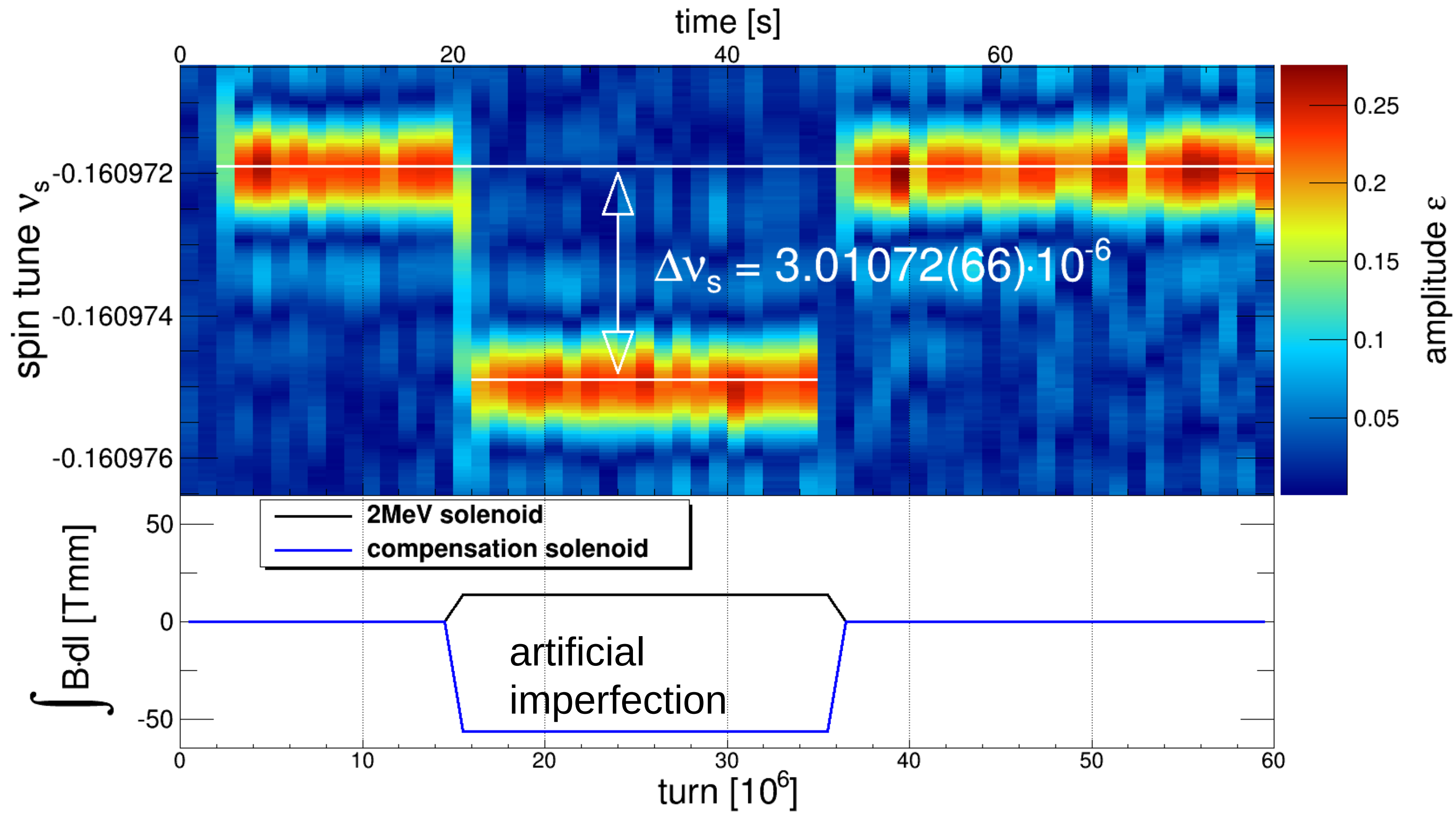






see: Phys.Rev.Lett. 115, 094801 (2015)

Spin tune: probing field imperfections



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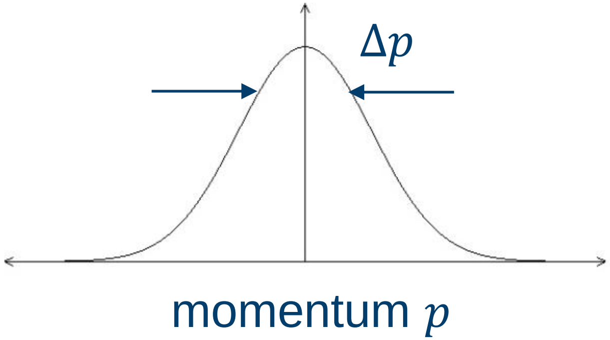
Spin Coherence Time (SCT)

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



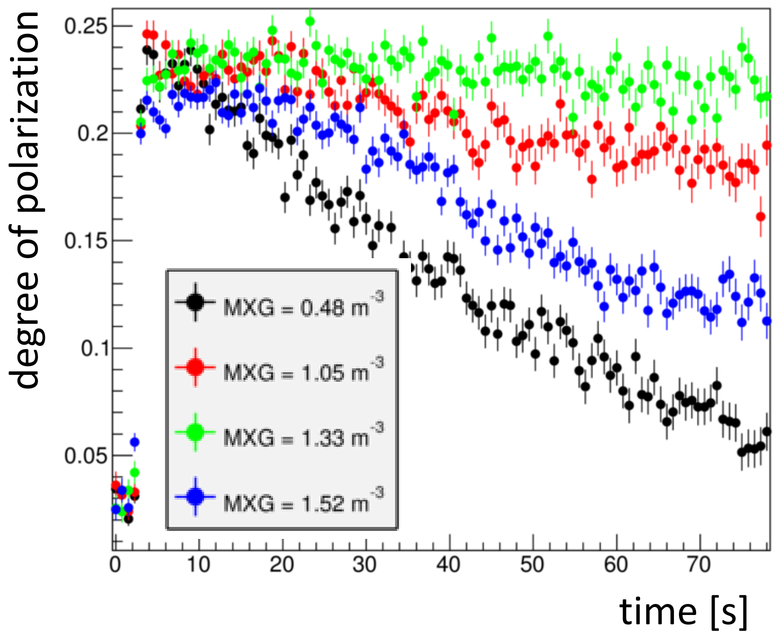
$$\frac{\Delta\gamma}{\gamma} = \overset{0.2}{\beta^2}\,\overset{10^{-3}}{\frac{\Delta p}{p}} \approx 10^{-4} = \frac{\Delta\nu}{\nu}$$

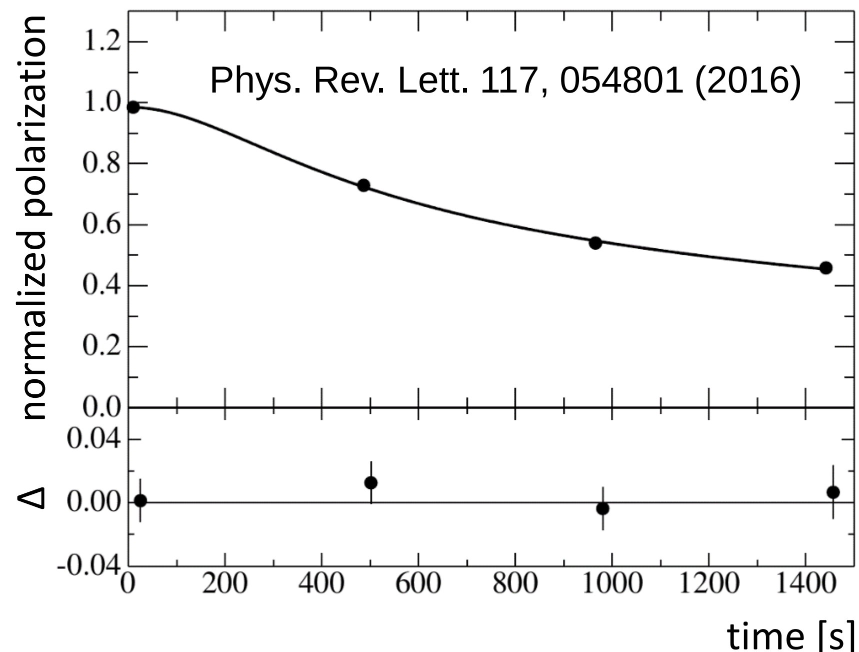
$$\Delta\nu \approx 10^{-4} \cdot 0.16 \approx 10^{-5}$$

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

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 $\rightarrow \tau \approx 20$ s
- correcting higher order effects using sextupoles
  and (pre-) cooling $\rightarrow \tau \approx 1000$ s





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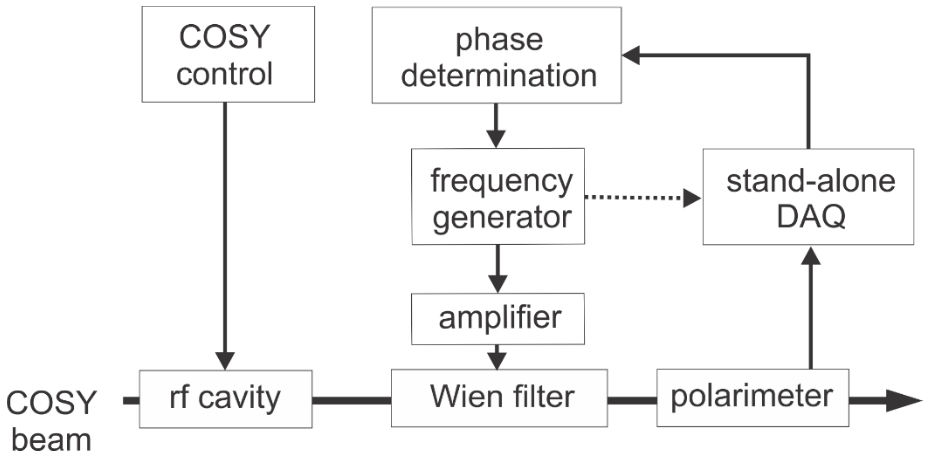
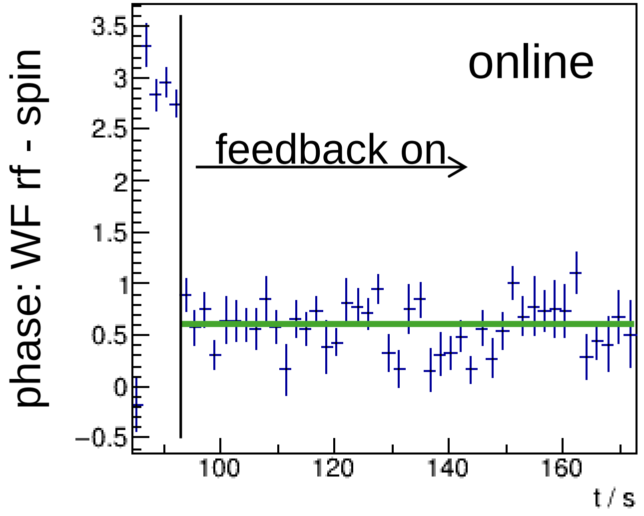
Spin tune: feedback system (phase lock)

Challenges:

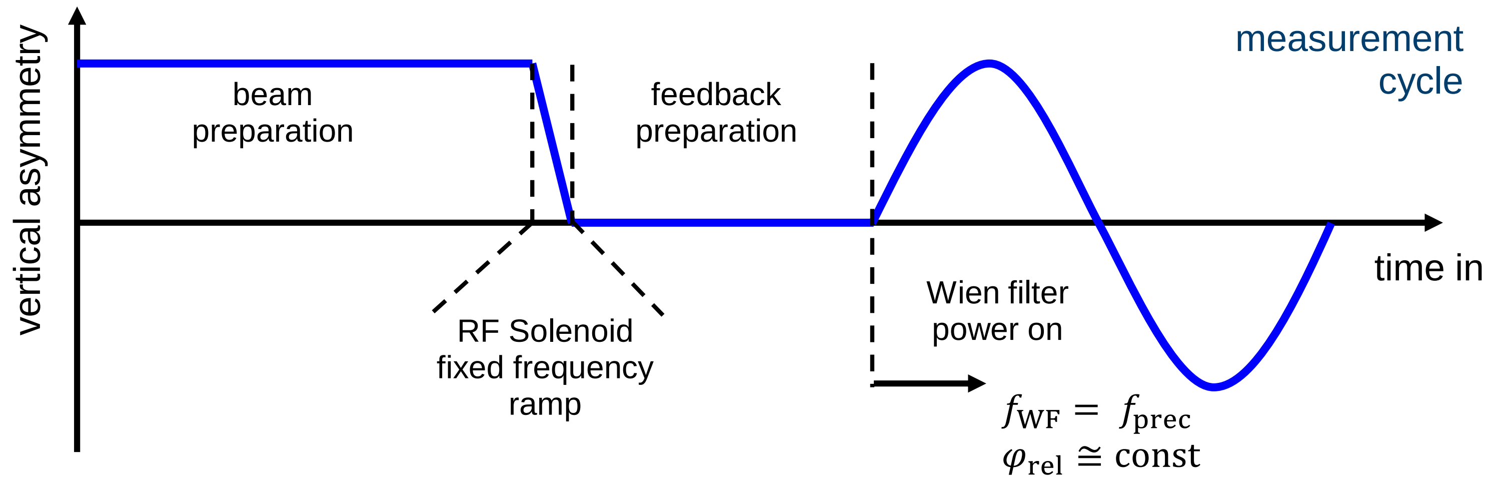
- maintain resonance frequency and phase between spin precession and Wien filter
- maintain frozen spin condition in a future dedicated ring

Implementation at COSY:



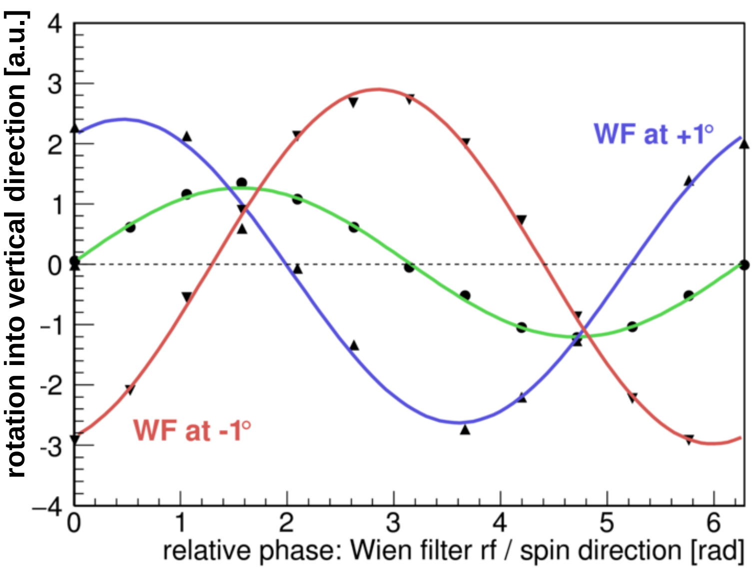


Measurements with the Wien filter



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



Summary

- EDMs sensitive to new sources of $\mathcal{CP}$ violation
- Mechanism for $\mathcal{CP}$ 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