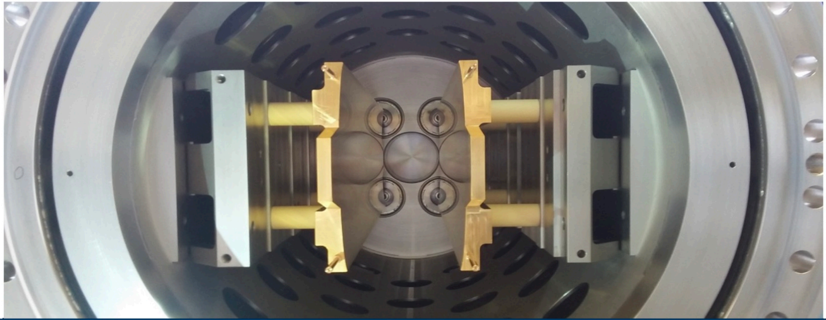


Master Talk

Polarisation Investigations for Storage Ring EDM Measurements

May 15 | Achim Andres

Member of the Helmholtz Association

RWTH AACHEN UNIVERSITY

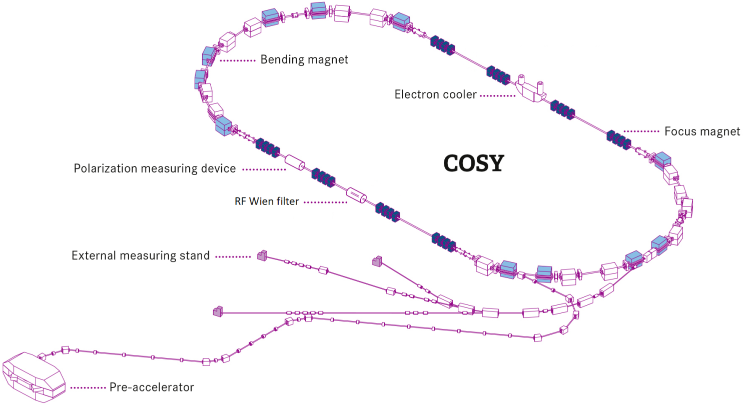
JEDI

JÜLICH Forschungszentrum

Contents

Cooler Synchrotron

- Circumference 184 m
- Magnetic Ring
- Polarised and unpolarised Deuterons and Protons
- $p = 0.3$ - 3.7 GeV/c
- Used for EDM Precursor Experiments



COSY Facility.

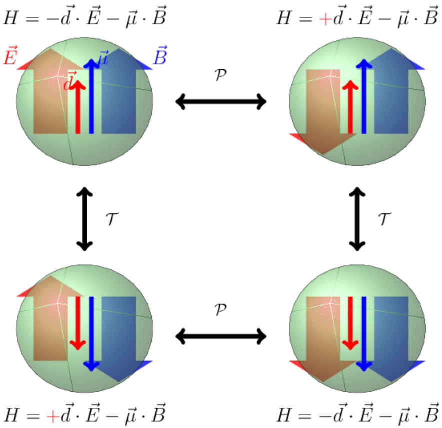
Motivation – Electric Dipole Moment

- EDM fundamental property of particles: $\vec{d} = d \cdot \vec{s}$
- Magnetic Dipole Moment $\vec{\mu} = \mu \cdot \vec{s}$

$$\hat{\mathcal{H}} = -d \cdot \vec{s} \cdot \vec{E} - \mu \cdot \vec{s} \cdot \vec{B}$$
$$\mathcal{P}(\hat{\mathcal{H}}) = +d \cdot \vec{s} \cdot \vec{E} - \mu \cdot \vec{s} \cdot \vec{B}$$
$$\mathcal{T}(\hat{\mathcal{H}}) = +d \cdot \vec{s} \cdot \vec{E} - \mu \cdot \vec{s} \cdot \vec{B}$$

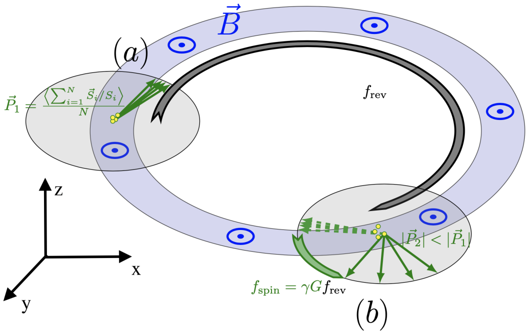
- According to CPT theorem: T violation = CP violation
- EDM violates both P and CP symmetry
- Neutron EDM:

$$d_n \begin{cases} \lesssim 1.8 \cdot 10^{-26}\ e \cdot \text{cm} & \text{Measured} \\ \approx 10^{-31}\ e \cdot \text{cm} & \text{SM Prediction} \end{cases}$$



Breach of symmetries.

Spin Tune & Polarisation



$$\text{Polarisation } \vec{P} = \frac{1}{N}\sum_{i=1}^{N} \vec{S}_i$$

$$p_V = p_z$$

$$p_H = \sqrt{p_x^2 + p_y^2}$$

$$\text{Spin Tune } \nu_s = \frac{\text{Spin Precession}}{\text{Turn}} = \gamma G_d$$

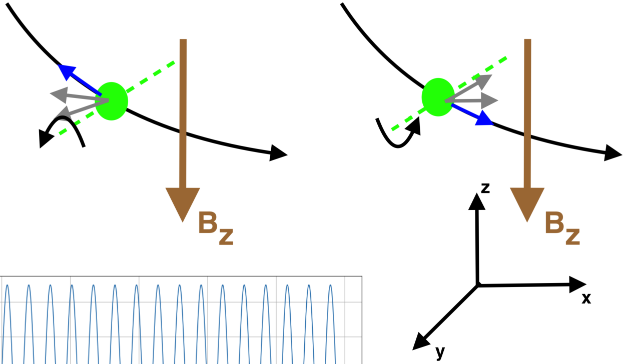
$$\nu_{s,\text{COSY}} = -0.16 \; (= 120 \text{ kHz} = |\nu_s| \cdot f_{\text{cosy}})$$

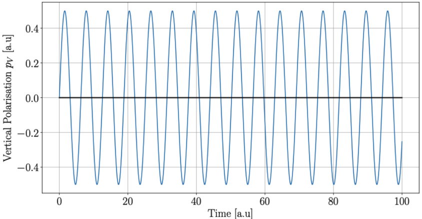
γ: Lorentz Factor

G_d: Anomalous Magnetic Moment (deuteron)

Measurement Principle – EDM

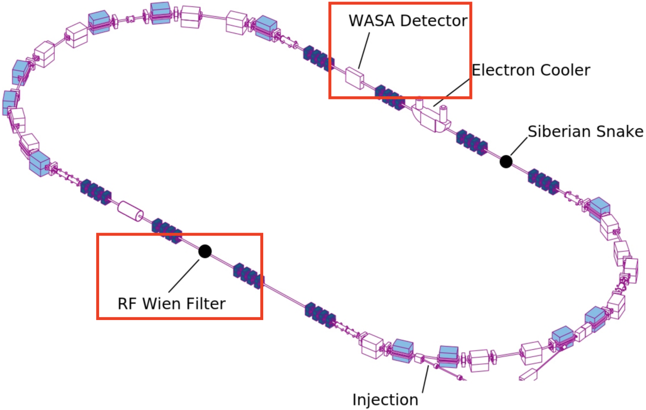
- Uniform polarisation rotation
- Tilt of the polarisation due to the EDM: 50% up and 50% down
- No net signal measurable
- EDM $\propto$ Amplitude





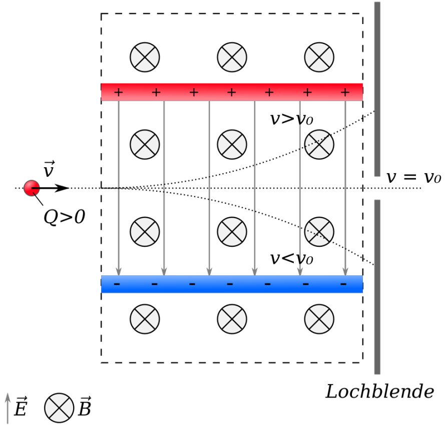
Spin
Particle Trajectory
Tilt of the Spin

Cosy


WASA Detector
Electron Cooler
Siberian Snake
RF Wien Filter
Injection

COSY.

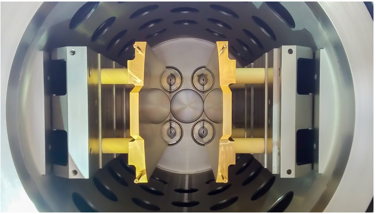
Wien Filter



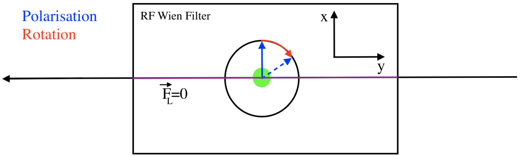
Wien Filter.

- $\vec{E} \perp \vec{B} \perp$ Beam
- $\vec{F_L} = q(\vec{E} + \vec{v} \times \vec{B})$
- Matched Point: $\vec{F_L} = 0$
- $v_0 = \frac{E}{B}$

Radio frequency Wien Filter



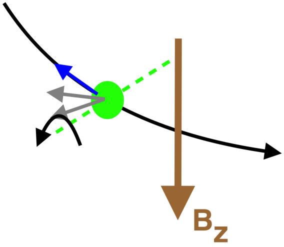
RF Wien Filter.

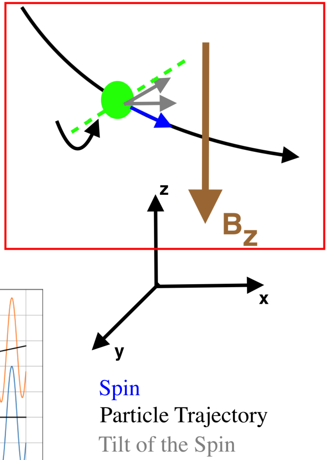


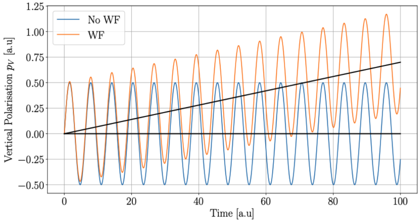
- Horizontal polarised beam
- Ideal case: no influence on the beam
- Works on the same frequency as the spin tune $f_{\mathrm{WF}} = f_{\mathrm{spins}}$
- Polarisation rotation around *z*-axis
- Phase Feedback: Fixed Phase relation between $f_{\mathrm{WF}} = f_{\mathrm{spins}}$

Measurement Principle – EDM – Wien Filter

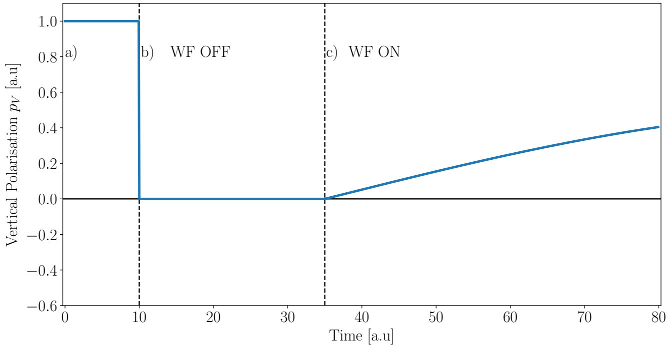
- RF WF rotates polarisation around the vertical axis
- Right (or left) scenario is preferential
- Vertical Polarisation accumulates





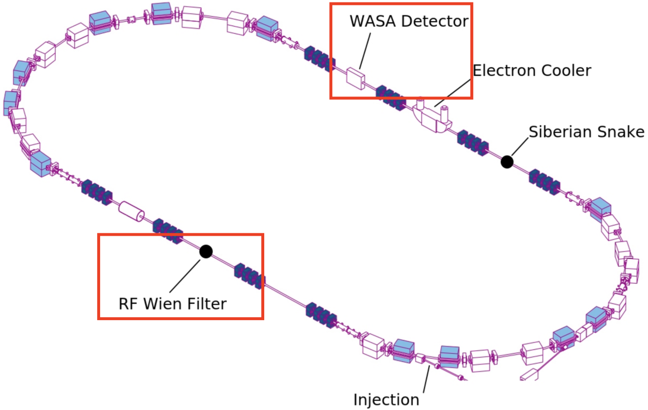


Measurement Pinciple - A Typical Cycle



a) Beam preparation (bunching & cooling)
b) Feedback preparation: $f_{\mathrm{WF}} = f_{\mathrm{spins}}, \phi_{\mathrm{rel}} = \mathrm{const}$
c) WF on: Vertical polarisation accumulates due to EDM + systematics

Cosy


WASA Detector
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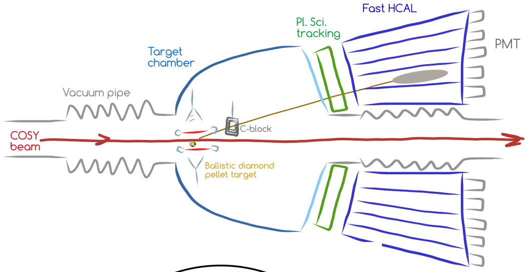
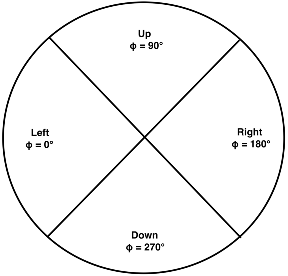
COSY.

Polarimetry





$$\dot{N}_X = \alpha\sigma(\phi; p_H, p_V)\mathcal{L}$$

$$X : \text{Up, Down, Left, Right}$$

$$\dot{N}_{\uparrow\downarrow} \propto 1 \mp \frac{3}{2} p_H A \cos(2\pi\nu_s n + \varphi)$$

$$\dot{N}_{\leftrightarrows} \propto 1 \mp \frac{3}{2} p_V A$$

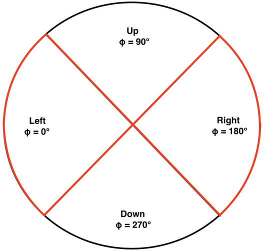
A: Analysing Power

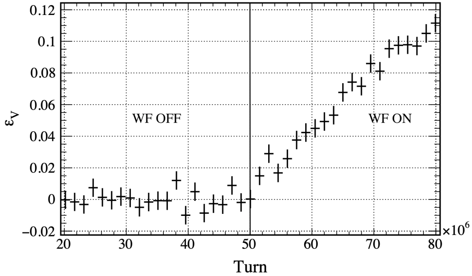
p_V, p_H: Vertical and Horizontal Polarisation

ν_s : Spin Tune

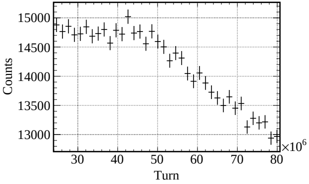
$\epsilon_V = \frac{3}{2} A p_V$ & $\epsilon_H = \frac{3}{2} A p_H$

Polarimetry – Vertical Polarisation

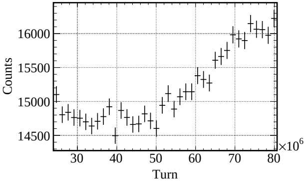




- $\dot{N}_{\leftrightarrows} \propto 1 \mp \frac{3}{2} p_V A = 1 \mp \epsilon_V$
- $\frac{N_L - N_R}{N_L + N_R} = \epsilon_V$
- Signal $\propto$ EDM + Systematics

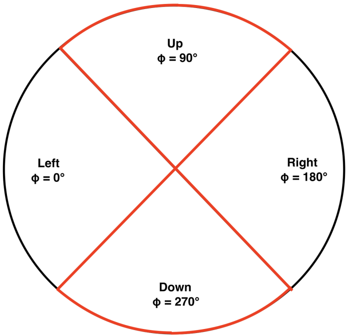


Left Detector



Right Detector

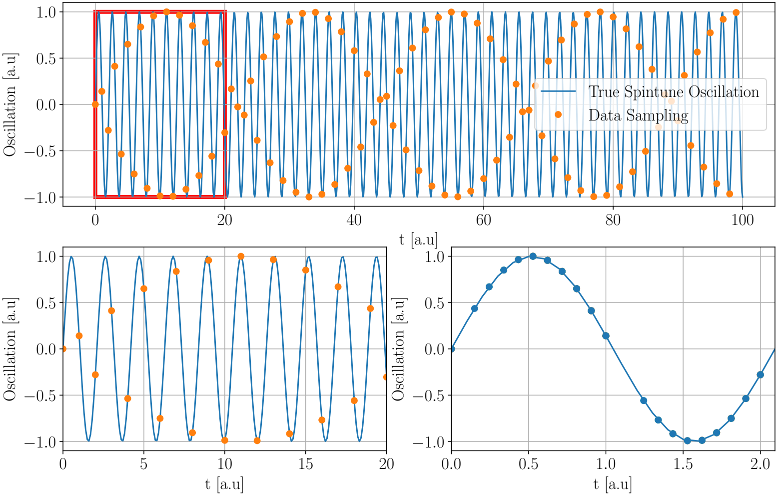
Polarimetry – Horizontal Polarisation



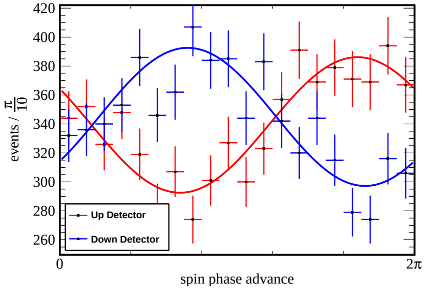
$$\dot{N}_{\uparrow\downarrow} \propto 1 \mp \epsilon_H \cos(2\pi\nu_s n + \varphi)$$

- **Problem:** $\nu_s \approx -0.16 \mathrel{\hat{\approx}} 120$ kHz and Detector Rate 5000 Hz
- One data point every 24 rotations
- No direct fit possible with ν_s as a parameter
- Other methods are needed!

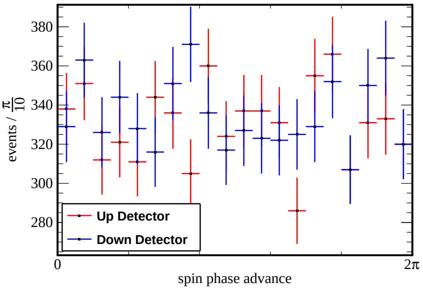
Combined Detectors – Mapping Method



Mapping Method



$\nu_s = 0.1609706675$



$\nu_s = 0.1609702$

- Spin Phase Advance: $\varphi_s = 2\pi\nu n$
- Map into a single oscillation period
- $\dot{N}_{\uparrow\downarrow} = \alpha\mathcal{L} \cdot \left(1 \mp \epsilon_H \cos(\omega_s + \varphi)\right)$

Horizontal Polarisation & Phase

$$\dot{N}_{\uparrow\downarrow} = \alpha\mathcal{L} \cdot \left(1 \mp \epsilon_H \cos(2\pi\nu_s n + \varphi)\right)$$

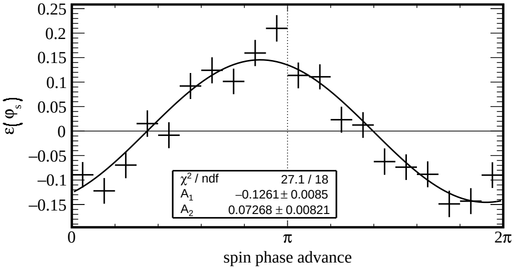
$$\epsilon\left(\varphi_{\mathrm{s}}\right) = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \epsilon_H \sin\left(\varphi_{\mathrm{s}} + \varphi\right)$$

- Fit asymmetry with
  $\epsilon\left(\varphi_s\right) = A_1 \sin\left(\varphi_s\right) + A_2 \cos\left(\varphi_s\right)$

  $$\epsilon_H = \sqrt{A_1^2 + A_2^2} = 0.15 \pm 0.01$$

  $$\varphi = \mathrm{atan}(A_2/A_1) = (-1.05 \pm 0.06)\ \mathrm{rad}$$

- Result is independent from luminosity, acceptances,..



Horizontal Polarisation & Phase

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  $\epsilon(\varphi_s) = A_1 \sin(\varphi_s) + A_2 \cos(\varphi_s)$

$$\epsilon_H = \sqrt{A_1^2 + A_2^2} = 0.15 \pm 0.01$$

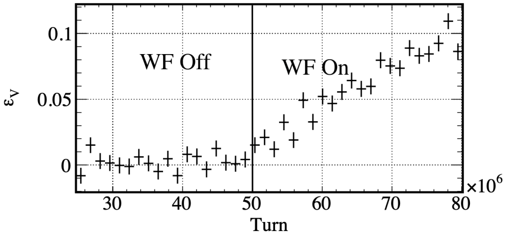
- Polarisation:

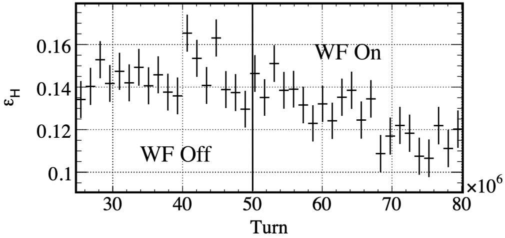
$$\vec{P} = \frac{1}{N}\sum_{i=1}^{N} \vec{S_i}$$

$$p_V = p_z$$

$$p_H = \sqrt{p_x^2 + p_y^2}$$

- Result is independent from luminosity, acceptances,..



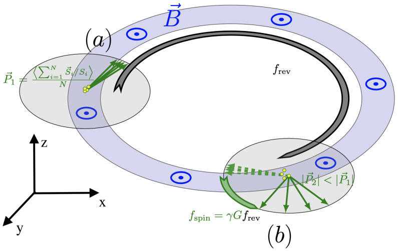


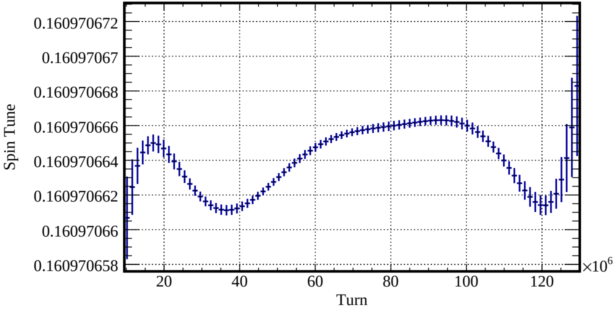
Spin Tune

- Fit asymmetry with
  $\epsilon(\varphi_s) = A_1 \sin(\varphi_s) + A_2 \cos(\varphi_s)$

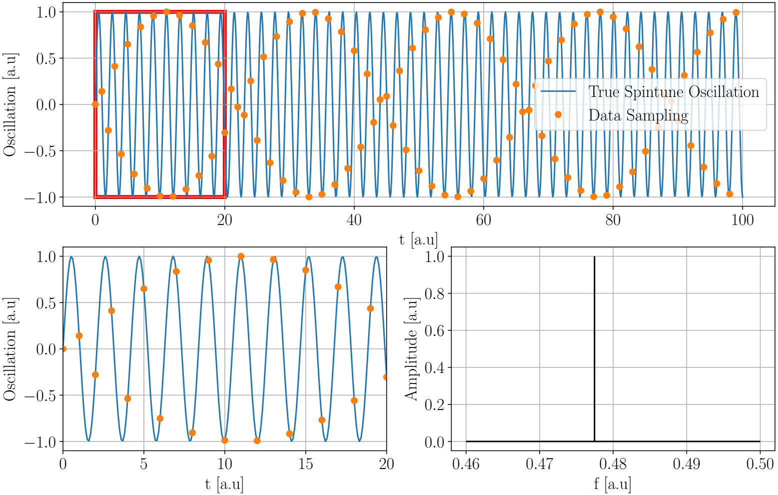
  $\varphi = \text{atan}(A_2/A_1) = (-1.05 \pm 0.06)$ rad

- Change of phase leads to the spin tune ν_s



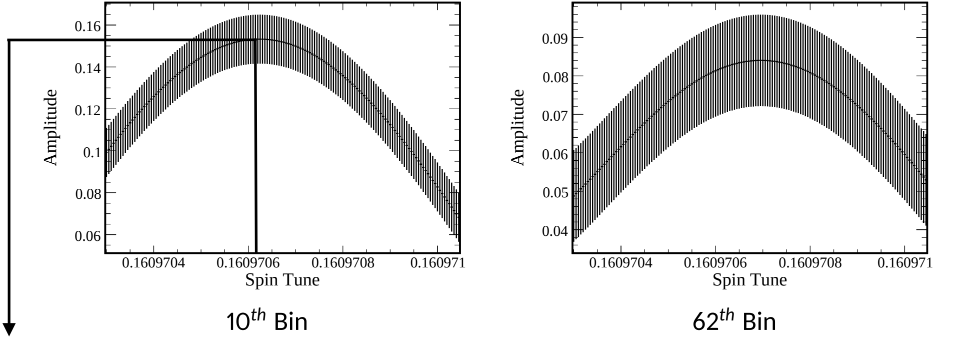


Fourier Method



Fourier Spectra

$$\dot{N}_{\uparrow\downarrow} \propto \mathcal{L} \cdot \left(1 \pm \epsilon_H \cos(2\pi\nu_s n + \varphi)\right)$$

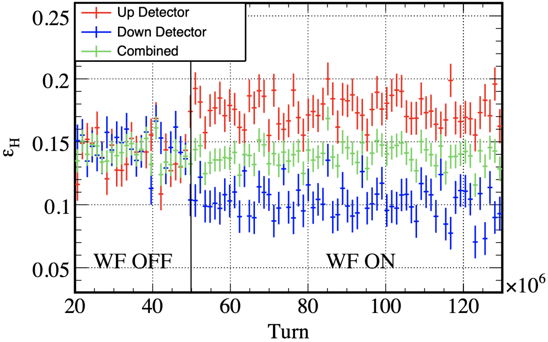


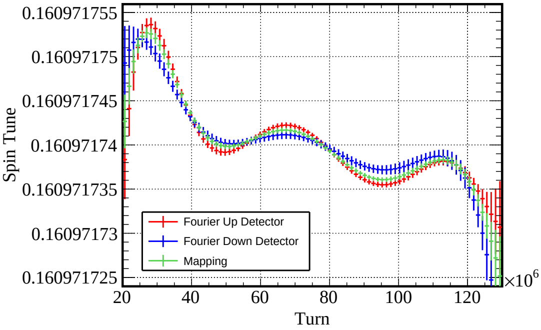
10^{th} Bin

62^{th} Bin

- Fourier Amplitudes = ϵ_H
- For both detectors up and down
- (Oscillating) Luminosity effects **don't** cancel out

Comparison: Mapping – Fourier



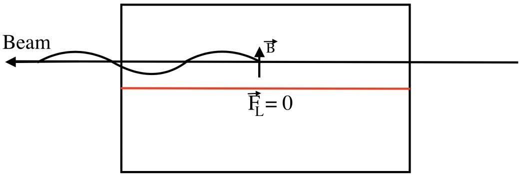


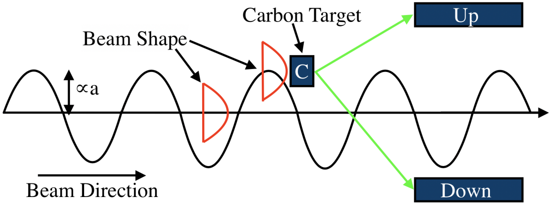
- Nonmatching Results when turning on the RF Wien Filter
- Luminosity Independent – Rest: Luminosity Dependent

Mismatch of the RF Wien Filter

- Everytime the WF rotates the polarisation, it excites beam oscillations, when $\vec{F}_L \neq 0$ at the beam position
- Osc. $\mathcal{L}$: $\mathcal{L}_{\text{osc}} = \mathcal{L}_{\text{COSY}} \cdot (1 + a \cos(\omega_s n))$
- Change of count rates: $\dot{N} = \alpha \mathcal{L} \sigma$

$$\dot{N}_{\text{Up}} \propto (1 + a\cos(\omega_s n)) \cdot (1 - \epsilon_H \cos(\omega_s n + \varphi_s))$$
$$\dot{N}_{\text{Down}} \propto (1 + a\cos(\omega_s n)) \cdot (1 + \epsilon_H \cos(\omega_s n + \varphi_s))$$
$$\dot{N}_{\text{Left}} \propto (1 + a\cos(\omega_s n)) \cdot (1 + \epsilon_V)$$
$$\dot{N}_{\text{Right}} \propto (1 + a\cos(\omega_s n)) \cdot (1 - \epsilon_V)$$



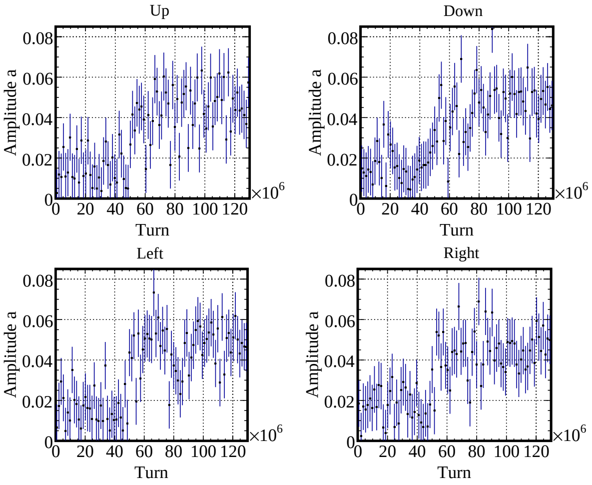


Unpolarised Cycle

- Change of count rates: $\dot{N} = \alpha \mathcal{L} \sigma$

$$\begin{aligned} \dot{N}_{\text{Up}} &\propto 1 + a\cos(\omega_s n) \\ \dot{N}_{\text{Down}} &\propto 1 + a\cos(\omega_s n) \\ \dot{N}_{\text{Left}} &\propto 1 + a\cos(\omega_s n) \\ \dot{N}_{\text{Right}} &\propto 1 + a\cos(\omega_s n) \end{aligned}$$

- Unpolarised cycle: $\epsilon_V = \epsilon_H = 0$
- a is the same in all four detectors, because the luminosity changes on the target



Polarised Data with Phase Feedback

- Phase between RF Wien Filter and Polarisation Precession remains constant: $\varphi_s + \varphi_0$

$$\dot{N}_{\uparrow\downarrow} \propto \left(1 + a\cos(\omega_s n + \varphi_s + \varphi_0)\right) \cdot \left(1 \mp \epsilon_H \cos(\omega_s n + \varphi_s)\right)$$

- Mapping

$$\epsilon\left(\varphi_s\right) = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \epsilon_H \cdot \sin(\varphi_s + \varphi)$$

- Fourier Amplitudes in Single Detectors:

$$A_{\uparrow\downarrow}(\omega = \omega_s) = \sqrt{a^2 + \epsilon_H^2 \mp 2a\epsilon_H \cos(\varphi_0)}$$

Polarised Data with Phase Feedback

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- Mapping

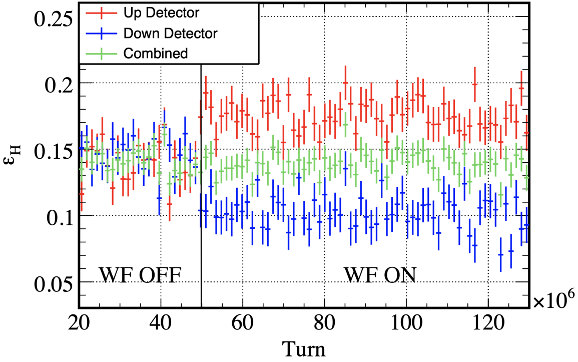
$$\epsilon\left(\varphi_s\right) = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = \epsilon_H \cdot \sin(\varphi_s + \varphi)$$

- Fourier Amplitudes in Single Detectors:

$$A_{\uparrow\downarrow}(\omega = \omega_s) = \sqrt{a^2 + \epsilon_H^2 \mp 2a\epsilon_H \cos(\varphi_0)}$$

- For $\varphi_0 = \pi$ rad

$$A_{\uparrow\downarrow} = |a \pm \epsilon_H|$$



Polarised Data with Phase Feedback

- Phase between RF Wien Filter and Polarisation Precession remains constant: $\varphi_s + \varphi_0$

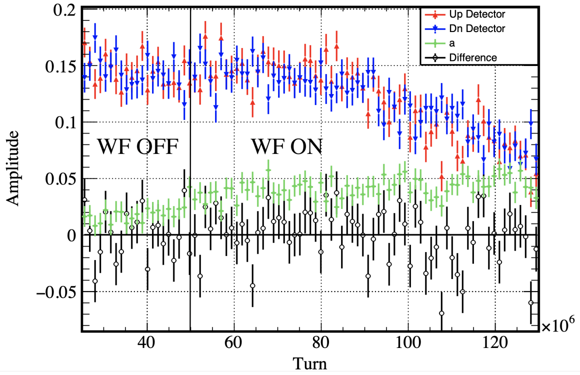
$$\dot{N}_{\uparrow\downarrow} \propto \left(1 + a\cos(\omega_s n + \varphi_s + \varphi_0)\right) \cdot \left(1 \mp \epsilon_H \cos(\omega_s n + \varphi_s)\right)$$

- Fourier Amplitudes in Single Detectors:

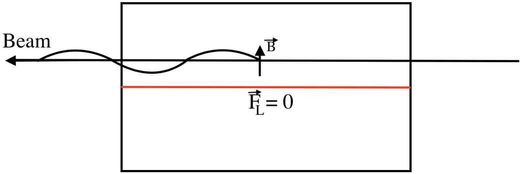
$$A_{\uparrow\downarrow}(\omega = \omega_s) = \sqrt{a^2 + \epsilon_H^2 \mp 2a\epsilon_H \cos(\varphi_0)}$$

- For $\varphi_0 = \pi/2$ rad

$$A_{\uparrow\downarrow} = \sqrt{a^2 + \epsilon_H^2}$$



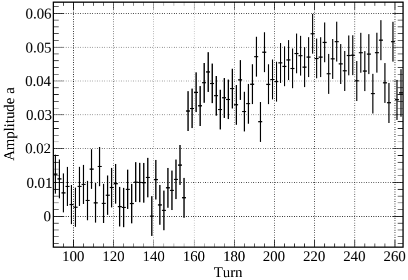
New Online Monitoring System



- Sum of counting rates

$$\dot{N}_{\mathrm{sum}} = \dot{N}_{\mathrm{up}} + \dot{N}_{\mathrm{down}} + \dot{N}_{\mathrm{left}} + \dot{N}_{\mathrm{right}} \propto 4 + 4a\cos(\omega_s n)$$

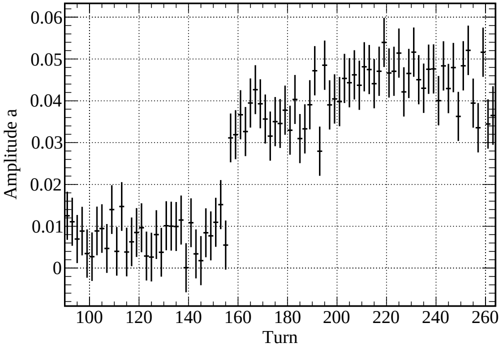
$$\dot{N}_{\mathrm{Up}} \propto (1 + a\cos(\omega_s n)) \cdot (1 - \epsilon_H \cos(\omega_s n + \varphi_s))$$
$$\dot{N}_{\mathrm{Down}} \propto (1 + a\cos(\omega_s n)) \cdot (1 + \epsilon_H \cos(\omega_s n + \varphi_s))$$
$$\dot{N}_{\mathrm{Left}} \propto (1 + a\cos(\omega_s n)) \cdot (1 + \epsilon_V)$$
$$\dot{N}_{\mathrm{Right}} \propto (1 + a\cos(\omega_s n)) \cdot (1 - \epsilon_V)$$



- Monitor *a* while adjusting the Wien Filter field

Summary

- $\vec{F}_L \neq 0 \ \Rightarrow$ Wien Filter excites beam oscillations
- Oscillating Count Rates in the Polarimeter
- A **New Online Monitoring** tool allows to observe the change of luminosity
- Adjust the electromagnetic field inside the RF Wien Filter so that $\vec{F}_L = 0$
- Never look at only one detector for spintune, phase and polarisation, as luminosity effects do not cancel out



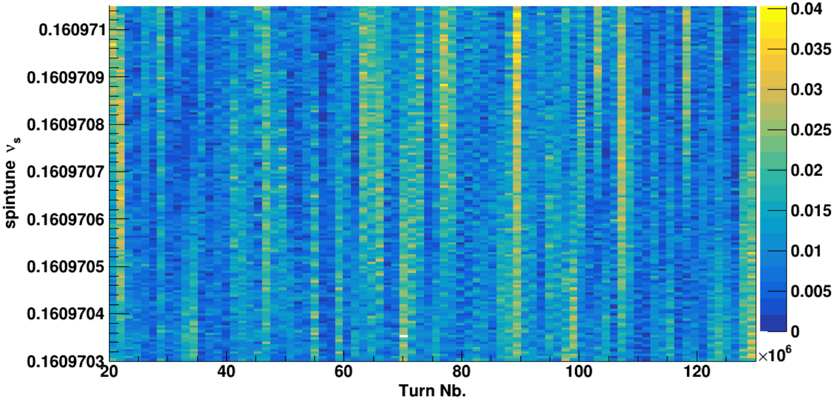
Fourier Method

$$N_{\uparrow\downarrow} \propto 1 \mp \frac{3}{2} p_{xy} A \cos(2\pi\nu_s n) + \varphi_s)$$

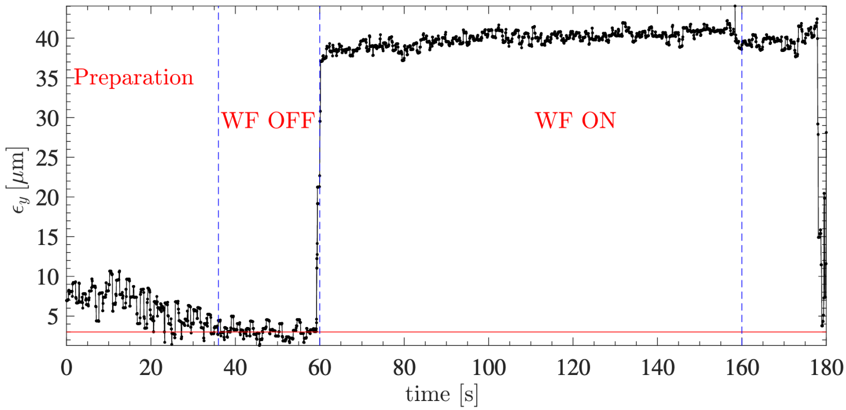
Scan $\nu_k \in \{\nu_{\min}, \nu_{\max}\}$ around 0.16 for both detectors

$$\begin{aligned}
a_{\nu_k} &= \frac{1}{N_{ev}} \sum_{n_{ev}=1}^{N_{n_{ev}}} \cos(2\pi\nu_k n(n_{ev})) \\
b_{\nu_k} &= \frac{1}{N_{ev}} \sum_{n_{ev}=1}^{N_{n_{ev}}} -\sin(2\pi\nu_k n(n_{ev})) \\
\epsilon_{\nu_k} &= \sqrt{a_{\nu_k}^2 + b_{\nu_k}^2}
\end{aligned}$$

Amplitudes – Unpolarized Cycle – Mapping Method

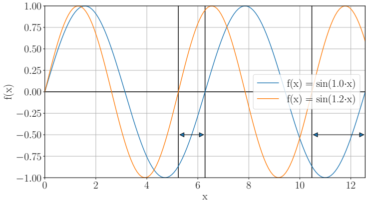


BPM Method

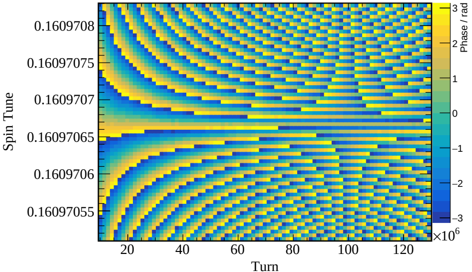


Preparation
WF OFF
WF ON
ϵ_y [μm]
40
35
30
25
20
15
10
5
0
20
40
60
80
100
120
140
160
180
time [s]

Spin Tune



- Phase: Frequency Difference of assumed and true Spin Tune



Spin Tune

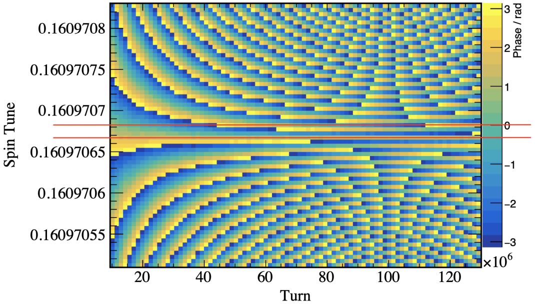
- Phase: Frequency Difference of assumed and true Spin Tune
- Spin Tune

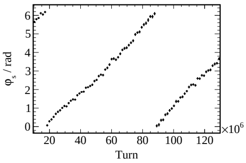
$$\nu_s(n) = \nu_s^0 + \frac{1}{2\pi}\frac{\partial \varphi}{\partial n}$$

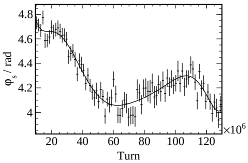
- Fit Phase:

$$\varphi_s = \sum_{i=0}^{8} a_i n^i.$$

$$\frac{\partial \varphi_s}{\partial n} = \sum_{i=0}^{8} a_i n^{i-1} i$$







Spin Tune

- Phase: Frequency Difference of assumed and true Spin Tune
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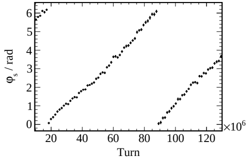
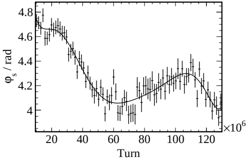
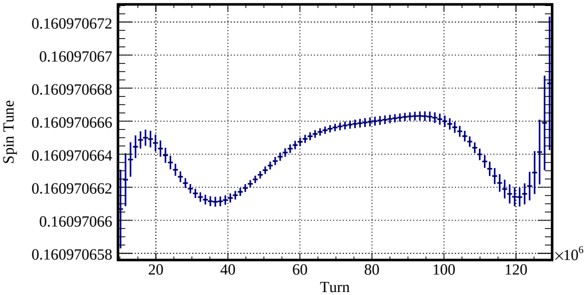
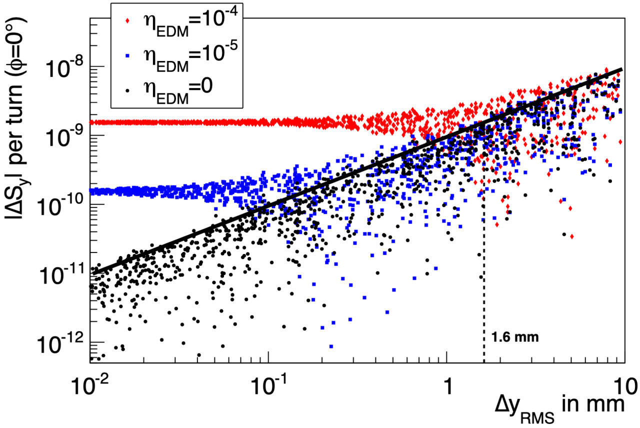






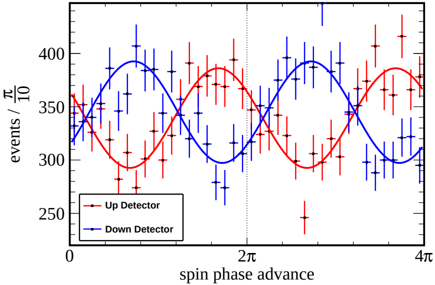
Systematic Errors

- Simulation: Beam offsets generated with randomized gaussian vertical quadropole shifts
- $d = \eta \frac{q\hbar}{2mc}$
- For a certain Beam offset, the signal becomes indistinguishable from EDM
- A precise orbit is crucial for an EDM measurement

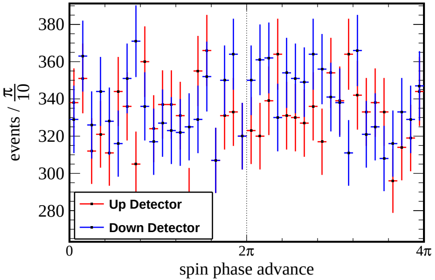


EDM simulations [?].

Mapping Method



$\nu_s = 0.1609706675$



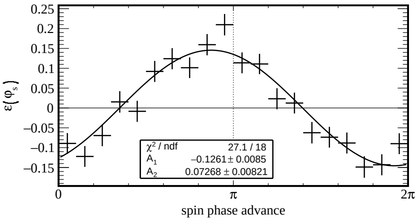
$\nu_s = 0.1609702$

- Spin Phase Advance: $\varphi_s = 2\pi\nu n$
- Map into a 4π oscillation period $\varphi_s = 2\pi\nu n \mod 4\pi$
- $N_{\uparrow\downarrow} \propto 1 \mp \epsilon_H \cos(\omega_s + \varphi)$

Horizontal Polarisation & Phase

$$N_X^{\pm}(\varphi_s) = \begin{cases} N_X(\varphi_s) \pm N_X(\varphi_s + 3\pi) & 0 \leq \varphi_s < \pi \\ N_X(\varphi_s) \pm N_X(\varphi_s + \pi) & \pi \leq \varphi_s < 2\pi \end{cases}$$

$$\begin{aligned} \epsilon(\varphi_s) &= \frac{N_U^-(\varphi_s) - N_D^-(\varphi_s)}{N_U^+(\varphi_s) + N_D^+(\varphi_s)} \\ &= \frac{3}{2} p_{xz} \frac{\overline{\sigma_0}_U \overline{A_y}_U - \overline{\sigma_0}_D \overline{A_y}_D}{\overline{\sigma_0}_U + \overline{\sigma_0}_D} \sin(\varphi_s + \varphi) \\ &= \epsilon_H \sin(\varphi_s + \varphi) \end{aligned}$$



- Fit asymmetry with
  $\epsilon(\varphi_s) = A_1 \sin(\varphi_s) + A_2 \cos(\varphi_s)$

  $$\epsilon_H = \sqrt{A_1^2 + A_2^2} = 0.15 \pm 0.01$$

  $$\varphi = \text{atan2}(A_2, A_1) = (-1.05 \pm 0.06)\ \mathrm{rad}$$

- Result is independent from luminosity, acceptances,..

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$$\begin{aligned} \epsilon(\varphi_\mathrm{s}) &= \frac{N_\mathrm{U}^{-}(\varphi_\mathrm{s}) - N_\mathrm{D}^{-}(\varphi_\mathrm{s})}{N_\mathrm{U}^{+}(\varphi_\mathrm{s}) + N_\mathrm{D}^{+}(\varphi_\mathrm{s})} \\ &= \frac{3}{2} p_{xz} \frac{\overline{\sigma_0}_U \overline{A_y}_U - \overline{\sigma_0}_D \overline{A_y}_D}{\overline{\sigma_0}_U + \overline{\sigma_0}_D} \sin(\varphi_\mathrm{s} + \varphi) \\ &= \epsilon_H \sin(\varphi_\mathrm{s} + \varphi) \end{aligned}$$

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