High Precision Spin Manipulation at COSY

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Forschungszentrum Jülich
1 Spin Motion in a Storage Ring
2 COSY as Spin Physics R&D Facility
3 Measurements: Horizontal Polarization
4 Measurements: Vertical Polarization
5 Conclusion
Spin Motion in a Storage Ring

Thomas-BMT Equation: \( \frac{d\vec{S}}{dt} = \vec{S} \times \vec{\Omega} \)

\[
\vec{\Omega} = \frac{q}{m} \left( (1 + \gamma G)\vec{B}_\perp + (1 + G)\vec{B}_\parallel - \left( \frac{\gamma}{\gamma + 1} + \gamma G \right) \vec{\beta} \times \frac{\vec{E}}{c} \right)
\]
Free Precession

Thomas-BMT Equation: \[ \frac{d\vec{S}}{dt} = \vec{S} \times \vec{\Omega} \]

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- ideal ring: only main bending dipoles
- additional spin precession per turn due to anomalous magnetic moment \( G \)
- spin tune \( \nu_S = \gamma G \) is relative number of precessions per turn
  - vertical polarization component \( S_y \) is constant

\[ \vec{B}_{\text{main}} \parallel \hat{y} \]

\[ \vec{\beta} \parallel \hat{z} \]
Driven Oscillation

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\]

- additional perturbation field leads to tilt of precession axis
- oscillating RF field in phase with spin precession will lead to accumulation of spin kicks
  \( \Rightarrow \) rotation of \( \vec{S} \) in vertical plane
  \( \Rightarrow \) oscillation of \( S_y \)
- resonant at all side bands \( f_S = |n + \nu_s|f_{\text{rev}}; \ n \in \mathbb{Z} \)
- resonance strength is defined as vertical spin rotation per revolution
Driven Oscillation

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COSY as Spin Physics R&D Facility

RF solenoid

RF ExB dipole

experiments with $\vec{d}$ @ 970 MeV/c

$G = -0.142 \Rightarrow \gamma G = -0.161$

$f_{\text{rev}} = 750 \text{ kHz} \Rightarrow f_{S} = 120 \text{ kHz}$

$\varepsilon_{x,y}$ and $\frac{\Delta p}{p}$ control beam cooling*

fast, continuous polarimetry

polarized source

[* → talk by V. Kamerdzhiev]
Spin Motion in a Storage Ring

COSY as Spin Physics R&D Facility

Measurements: Horizontal Polarization

Measurements: Vertical Polarization

Conclusion
Fast Polarimetry

- massive carbon target as defining aperture, use slow extraction
- beam polarization ⇔ average over all particles’ spins
⇒ asymmetries in $^{12}\text{C}(\vec{d}, d)$:

$$P_y \propto \epsilon_{lr} = \frac{N_{\text{left}} - N_{\text{right}}}{N_{\text{left}} + N_{\text{right}}}; \quad P_x \propto \epsilon_{ud} = \frac{N_{\text{up}} - N_{\text{down}}}{N_{\text{up}} + N_{\text{down}}}$$

- since 2012: high resolution timestamping for every event*

Horizontal Polarization Measurement

- use RF flipper to rotate polarization in horizontal plane
- accumulate data in time bins
- time stamping ⇒ determination of up-down-asymmetry signal in every bin:
  \[ P_x(t) \propto \tilde{\epsilon} \sin(2\pi \nu_s f_{\text{rev}} t + \phi) \]
- amplitude \( \tilde{\epsilon} \) corresponds horizontal polarization

\[ \begin{align*}
\text{amplitude} \quad \tilde{\epsilon} \\
0.0 & \quad 0.1 & \quad 0.2 & \quad 0.3
\end{align*} \]
\[ \begin{align*}
\text{spin tune} \quad \nu_s^0 \\
0.160970 & \quad 0.160975 & \quad 0.160980 & \quad 0.160985
\end{align*} \]

[D. Eversmann, JEDI Collaboration]
Spin Tune Evolution

- fix determined spin tune to all other macroscopic bins
- observe phase evolution $\tilde{\phi}(t)$ over whole cycle
  $\Rightarrow$ correlation of data from all time bins
- total spin tune change over time given by derivative of phase $\tilde{\phi}$

$$\nu_s(t) = \nu_s^0 + \frac{1}{2\pi f_{\text{rev}}} \frac{d\tilde{\phi}}{dt} = 0.1609752 + \Delta\nu_s(t)$$

- spin tune average over $\approx 100$ s cycle determined to $10^{-9}$ (!)

![Graph of phase vs time and spin tune change over time](image)

[D. Eversmann, JEDI Collaboration]
Long Time Stability

\[ \Delta \nu_s = 0.160 \, 975 \, 2 + \Delta \nu_s(t) \]

[D. Eversmann, JEDI Collaboration]
Amplitude Evolution ⇔ Spin Coherence Time

- spin precession frequency $f_s \approx \gamma G \cdot f_{\text{rev}}$
- averaging over particles’ spins ⇒ use bunching to fix $f_{\text{rev}}$ for all particles
- energy spread $\frac{\Delta \gamma}{\gamma}$ ⇒ spin tune spread
  ⇒ use beam cooling to minimize

[D. Eversmann, JEDI Collaboration]

Horizontal Asymmetry Run: 2042

$\epsilon_{ud} \propto e^{-\frac{t}{\tau_{\text{sct}}}}$

$\tau_{\text{sct}} \approx 20 \text{ s}$
Canceling 2\textsuperscript{nd} Order Effects with Sextupoles

- consider path lengthening effects

\[ \frac{\Delta \gamma}{\gamma} \propto \frac{\Delta L}{L} \propto (\langle x \rangle^2, \langle y \rangle^2, \delta^2) \]

- three independent families of COSY sextupoles at locations with large $\beta_x$, $\beta_y$, $D$ to compensate

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Horizontal Asymmetry Run: 2051

\[ \epsilon_{ud} \propto e^{-\frac{t}{\tau_{sct}}} \]

$\tau_{sct} \approx 400$ s

[D. Eversmann, JEDI Collaboration]
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The RF ExB dipole in Wien Filter Configuration

RF B dipole
\[ \int \hat{B}_x \, dz = 0.175 \, \text{T mm} \]

- ferrite blocks
- coil 8 windings
- length 560 mm

RF E dipole
\[ \int \hat{E}_y \, dz = 24.1 \, \text{kV} \]

- foil electrodes
- 50 µm stainless steel
- distance 54 mm
- length 580 mm

shielding Box

\[ \int \hat{F}_y \, dz = 0 \]

\[ e \hat{E}_y \]

\[ ec \beta \hat{B}_x \]
Driven Polarization Oscillation

- total spin flip only on resonance $\Rightarrow$ average polarization $\rightarrow$ 0
- minimum of vertical polarization oscillation frequency $f_{Py}$
- resonance strength is spin rotation per turn $\varepsilon = \frac{f_{Py, \text{min}}}{f_{rev}}$

$f_{Py, \text{min}} = 0.2012$ Hz at $f_{RF} = 871.427713$ kHz
Determination of Lorentz Force Compensation

- RF Wien filter at $f_{S,-1} = 871.4277$ kHz
- scan of betatron tune $q_y$ determines influence of beam oscillations
- RF-solenoid: $f_{Py} = \text{const.}$; RF-Wien-Filter: $f_{Py} = \text{const.}$
- RF-dipole: interference with driven coherent beam osc.

![Graph showing (2-qy)f_{rev} / kHz vs qy]

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Measurements: Vertical Polarization
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JEDI Collaboration: search for light hadrons’ permanent EDM

- accelerator ≡ experiment ⇒ aim for ultimate precision
  “conventional” accelerator

utilize polarization as diagnostic tool, examples:

- horizontal polarization:
  - spin tune measurements as high precision tool established
  - observation time for horizontal polarization pushed towards 1000 s mark

- vertical polarization:
  - precision spin manipulation with minimal beam disturbance
  - resonance strength determination by means of frequency measurement

[*talk by A. Lehrach]
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Spin Tune per Time Bin

- use RF flipper to rotate polarization in horizontal plane
- detector signal: \( N_{\text{up, down}}(t) \propto 1 \pm \sin(2\pi f_S t + \phi) \)
- \( f_S \approx \gamma G \cdot f_{\text{rev}} = 120 \text{ kHz}, \) but event rate only \( \approx 5 \text{ kHz} \)

\[ \Rightarrow \] detector event only every 25th oscillation period

[J. Pretz, JEDI Collaboration]
Spin Tune per Time Bin

- use RF flipper to rotate polarization in horizontal plane
- detector signal: $N_{\text{up, down}}(t) \propto 1 \pm \sin(2\pi f_S t + \phi)$
- $f_S \approx \gamma G \cdot f_{\text{rev}} = 120$ kHz, but event rate only $\approx 5$ kHz
  $\Rightarrow$ detector event only every 25th oscillation period
- time stamps $t \Rightarrow$ map all events of macroscopic bin into one assumed oscillation period $T_s \iff t' = \text{mod} \,(t, T_s)$

![Graph depicting the number of events over time](image)

[J. Pretz, JEDI Collaboration]
Spin Tune per Time Bin, cont.

1. Timestamps $t \Rightarrow$ map all events of macroscopic bin into one assumed oscillation period $T_s \Leftrightarrow t' = \text{mod} (t, T_s)$
2. Calculate asymmetries in one time period and fit oscillation
3. Extract amplitude $\tilde{\epsilon} \propto$ polarization from fit

\[ \phi_s = 2\pi \frac{t'}{T_s} \]

\[ \epsilon(\phi_s) = \tilde{\epsilon} \cdot \sin(\phi_s + \tilde{\phi}) \]

[D. Eversmann, JEDI Collaboration]
Spin Tune per Time Bin, cont.

1. timestamps \( t \Rightarrow \) map all events of macroscopic bin into one assumed oscillation period \( T_s \iff t' = \text{mod}(t, T_s) \)
2. calculate asymmetries in one time period and fit oscillation
3. extract amplitude \( \tilde{\epsilon} \propto \) polarization from fit
4. vary value of \( T_s \), repeat
5. best spin tune manifests as maximum in spectrum of \( \nu_s = \frac{2\pi}{T_s f_{\text{rev}}} \)

[D. Eversmann, JEDI Collaboration]