Towards JEDI@COSY: systematic studies of spin dynamics in preparation for the EDM searches

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Forschungszentrum Jülich, Germany
Landau Institute for Theoretical Physics, Russia
Samara State University, Russia
Outline

• Exploring the COSY ring for Electric Dipole Moment (EDM) studies (JEDI - Jülich Electric Dipole moment Investigations)

• Imperfection background to EDM spin precession

• Mapping the spin tune with static solenoids

• Summary
Cooler Synchrotron COSY in Jülich

RF Devices for Spin Manipulations

EDDA Polarimeter

Solenoids

Polarized Protons / Deuterons

Electron Cooler

Momentum up to 3.7 GeV/c,

Circumference 184 m
Spin Motion in Storage Ring

- **Thomas BMT eqn. for the Magnetic Dipole Moment (MDM)**

\[
\frac{d\vec{S}}{dt} = \vec{S} \times \vec{\Omega}_{MDM}
\]

\[
\vec{\Omega}_{MDM} = \frac{q}{m} \left( G \vec{B} - \left( G - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} - \frac{G\gamma}{\gamma + 1} \vec{\beta} (\vec{\beta} \cdot \vec{B}) \right)
\]

**Spintune** := Number of spin turns relative to particle turns, for the ideal pure magnetic ring like COSY:

\[
\nu_s := \frac{|\vec{\Omega}_{MDM}|}{\omega_{\text{rev}}} = \frac{q}{m} \frac{GB}{q/m/\gamma B} = \gamma G
\]

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a.saleev@fz-juelich.de
Spin Precession by EDM in Pure Magnetic Ring

- If particle has \( d \neq 0 \), T-BMT equation takes form
  \[
  \frac{d \v{S}}{dt} = -\frac{q}{m} \left( G \v{B} + \eta (\v{\beta} \times \v{B}) \right) \times \v{S}(t)
  \]
- Interaction of the EDM with the motional E-field tilts the stable spin axis:
  \[
  \v{n}_{co} = (\v{e}_x \sin \xi + \v{e}_y \cos \xi)
  \]
  \[
  \tan \xi = -\frac{\eta}{G} \beta, \quad \eta = d \frac{m}{q}
  \]
- The JEDI Collaboration aims at a first direct measurement of the deuteron and proton Electric Dipole Moment (EDM) at COSY
- JEDI looks forward to the RF E-field induced EDM rotation without excitation of the coherent betatron oscillations. Example: RF Wien-Filter, EDM signal comes from ring


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Imperfection In-plane Fields

- A current task for JEDI: exploring the EDM dynamics and systematic limitations of the EDM searches at all magnetic rings

- Misalignment of any magnetic elements produces the in-plane imperfection magnetic fields

- Imperfection spin kicks perturb $\vec{n}_{co}$:
  \[ \vec{n}_{co} = (\vec{e}_x c_1 + \vec{e}_y c_2 + \vec{e}_z c_3) \]

- The nonvanishing $c_1$ and $c_3$ generate a background to the EDM-signal of the ideal imperfection-free case
  \[ c_1 = \sin \xi, \quad c_3 = 0 \]

- The challenge is to control background (for example with the accuracy $c_1 \sim 10^{-6} \text{ rad}$ would amount to sensitivity for $d = 10^{-20} \text{ e} \cdot \text{cm}$)
EDDA Polarimeter

• **Left-Right** asymmetry
  ⇒ *vertical* polarization
  \[ P_V \propto \epsilon_{ver} = \frac{N_l - N_r}{N_l + N_r} \]

• **Up-Down** asymmetry
  ⇒ *horizontal* polarization
  \[ P_H \propto \epsilon_{hor} = \frac{N_{up} - N_{dn}}{N_{up} + N_{dn}} \]
Spin Tune Measurement

- Spin vector precesses with $f_{\text{Spin}} = \nu_s f_{\text{rev}}$ in the horizontal plane around spin closed orbit

- Asymmetry is given by:

$$\epsilon_{\text{hor}}(t) = \frac{N_{\text{up}} - N_{\text{dn}}}{N_{\text{up}} + N_{\text{dn}}} \approx AP(t) \sin(2\pi \nu_s f_{\text{rev}} t + \phi)$$

- What do we expect? (Deuterons, $p = 0.97$ GeV/c)
  \[\nu_s \approx 0.16, \quad f_{\text{rev}} = 750 \text{ kHz}\]
  - Spin precession frequency: $\nu_s \cdot f_{\text{rev}} \approx 120$ kHz

- Special spin tune analysis software resolves $\nu_s$ with an accuracy $10^{-8}$ in 1-second interval
Spin Tune Response to the Artificial Imperfections

- The spin tune is perturbed by small spin kicks $\sim a$ in the ring imperfection fields:
  \[ \nu_0 = G\gamma + O(a^2) \]
- The idea is to probe the in-plane imperfection fields by introducing well-known artificial imperfections.
- Apply artificial imperfections: spin kicks $\chi_1$ and $\chi_2$ by the compensation solenoids in e-coolers, located in both straight sections,
  \[ \nu_s = \nu_0 + O(c_3^2, (c_3^*)^2, \chi_1^2, \chi_2^2) \]
- Measure the spin tune shift w.r.t. applied spin kicks,
  \[ \Delta \nu_s(\chi_1, \chi_2) = \nu_s(\chi_1, \chi_2) - \nu_0 \]
Measurement of Spin Tune Shift

- Spin tune shift registered in the data analysis:

\[ \Delta v_s = 3.01072(66) \times 10^{-6} \]

- The spin tune shift was observed at \( t = [20, 45] \) s

1. Assume the values \( v_s \sim 0.16 \).
2. Fit \( A \) to asymmetry \( \epsilon_{\text{horr}} \).
The Spin Tune Mapping

Take multiple measurements with different $\chi_1$, $\chi_2$ and build a spin tune map $\Delta \nu_s(\chi_1, \chi_2)$:

Equal step size for $\chi_1$, $\chi_2$

$\Delta \chi = 0.002$

- Spin tune shift w.r.t. the solenoid spin kicks, $\Delta \nu_s \sim \chi_1^2$, $\Delta \nu_s \sim \chi_2^2$
The Spin Tune Mapping

- If the kicks are translated to:
  \[ y_+ = \frac{1}{2}(\chi_1 + \chi_2) \quad y_- = \frac{1}{2}(\chi_1 - \chi_2) \]
- then
  \[ \Delta \nu_s \propto -(y_- - a_-)^2, \quad \Delta \nu_s \propto (y_+ - a_+)^2 \]
- The distributions of the data points in \(y_\pm\) dimension share common parabolic features: equal curvature and extremum \(a_\pm\)
- It is a sign that the solenoids work as anticipated:
  \[ \Delta \nu_s(y_- = \text{const}) \]
  \[ y_- = 9.25 \text{ mrad} \]
  \[ y_- = 3.7 \text{ mrad} \]
Imperfection Strength

- Position of the saddle point measures projections of SCO, $c_3$ and $c_3^*$
- Strength of imperfection fields in the ring is at the level of $\approx 3 \text{ Tmm}$
- For an ideal ring, the saddle point would be at $a_{\pm} = 0$

The fitted saddle point at #:

\[
\begin{align*}
a_+ &= -0.00111077 \pm 6.1 \cdot 10^{-8} \text{ rad} \\
a_- &= 0.00244326 \pm 2.1 \cdot 10^{-7} \text{ rad} \\
c_3 &= -0.00299124 \pm 1.8 \cdot 10^{-7} \\
c_3^* &= -0.00163653 \pm 7.1 \cdot 10^{-8}
\end{align*}
\]
The technique of spin tune measurement appears as a precision tool for the systematic analysis of the ring imperfections.

First high precision measurement of the imperfection fields at COSY.

The ultimate goal of the JEDI: to understand the EDM dynamics in storage rings as a prerequisite to the construction of the dedicated storage ring for the EDM searches.
More Details About Spin Tune Analysis
Mapping the Events

1. Assume Spin Tune $\nu_{assumed}$
   
   $T_{assumed} = \frac{2\pi}{\nu_{assumed} f_{rev}}$

2. Map all events of a macroscopic time interval (2s) in first period:
   $t' = \text{mod}(t, T_{assumed})$

3. Fit asymmetry to first period
Fit Asymmetry to First Period

1. $T_{\text{assumed}}$

2. Mapping events

3. Fit asymmetry to first period

$f(\phi_s) = A \cdot \sin(\phi_s + \phi_0)$

$\chi^2/ndf = 18.4/17$

$A = 0.27 \pm 0.01$

$\phi_0 = 1.36 \pm 0.04$

Extract amplitude $A \propto \text{Polarisation}$
Find Correct Spin Tune

1. $T_{\text{assumed}}$
2. Mapping events
3. Fit asymmetry to first period

- Vary $T_{\text{assumed}}$ and repeat steps 1 to 3
- Plot extracted parameter $A$ vs $\nu_{\text{assumed}}$

- $\nu_{\text{max}}$ is correct spine tune in macroscopic time interval (2 s)
- $\nu_{\text{max}} = 0.160975 \pm 10^{-6}$

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a.saleev@fz-juelich.de
• $c_3$ is given after one of the solenoid, and $c_3^*$ after another

• Model function:

$$\Phi = \cos \pi (\nu_0 + \Delta \nu_s (y_+, y_-)) - \cos \pi \nu_0 =$$
$$- \left[ (E + \cos \pi \nu_0) \sin^2 \left(\frac{y_+}{2}\right) + \frac{1}{2} \sin \pi \nu_0 (c_3 + c_3^*) \sin y_+ +
(E - \cos \pi \nu_0) \sin^2 \left(\frac{y_-}{2}\right) + \frac{1}{2} \sin \pi \nu_0 (c_3 - c_3^*) \sin y_- \right]$$

• for a guidance:

$$\Phi \approx -\pi \Delta \nu_s \sin \pi \nu_0 \propto y_+^2, y_-^2$$

• $E \approx \cos \frac{\pi (\nu_1 - \nu_2)}{2} \approx 1$ is related to the difference of horizontal spin phase advances in the arcs

• The theory tells

$$\nu_1 - \nu_2 \sim O(c^2)$$
• The extremum of $\Phi$ is a saddle point at 
  \[ y_+, y_- = O(c_3, c_3^*) \]

• With solenoids only we are not sensitive to $c_1, c_1^*$

• Once $\nu_0$ has been determined, only $c_3$ and $c_3^*$ are the fit parameters