Measurement of Electric Dipole Moments of Charged Particles at Storage Rings
- Research and Development at COSY -

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on behalf of the JEDI Collaboration

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R&D at COSY

- maximizing spin coherence time
- precise spin tune determination
  (monitoring, study of imperfections, feedback systems, ..)
- rf-Wien filter
- development of high precision beam position monitors
  (e.g. SQUID based, final goal ≈ nm per cycle)
- electrostatic deflectors (goal: field strength > 10 MV/m)
- polarimeter development
- spin tracking in storage rings
  ...

see also: http://collaborations.fz-juelich.de/ikp/jedi
How to measure EDMs?

Common strategy for all EDM measurements:

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

For charged particles:

→ apply electric field in a storage ring

Ideal case:

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

Build-up of vertical polarisation

$s_\perp \propto |d|$
General case: spin motion

Thomas-BMT equation:

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

**MDM**

- \( \vec{\Omega} \): angular precession frequency
- \( G \): anomalous magnetic moment
- \( \vec{\beta} \): Lorentz factor

**EDM**

- \( d \): electric dipole moment
- \( m_0 \): rest mass
- \( c \): speed of light
- \( \hbar \): reduced Planck constant

In general:

- **magnetic moment** causes fast spin precession
- **“frozen spin”**: chose \( \gamma, \vec{B}, \vec{E} \) such that \( \Omega_{MDM} = 0 \)
COSY: pure magnetic ring

Thomas-BMT equation:

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

- polarized protons and deuterons up to 3.7 GeV/c available
- access to EDM via motional electric field \( \vec{\beta} \times \vec{B} \)
- requires additional means (e.g. rf \( E \) and \( B \) fields) to compensate \( G\vec{B} \) contribution

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

Thomas-BMT equation:

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

study spin tune \( \nu_S = \frac{|\vec{\Omega}|}{|\vec{\omega}_{\text{cycl}}|} = \gamma G \)

\( \rightarrow 2\pi \nu_S \): phase advance per turn

R&D with deuterons

\( p = 1 \text{ GeV/c} \)
\( G = -0.14256177(72) \)
\( \nu_S \approx -0.161 \rightarrow f_S \approx 120 \text{ kHz} \)
Experimental setup

1. inject and accelerate vertically polarized deuterons to $p = 1 \text{ GeV/c}$
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3. extract beam slowly (within 100 s) onto a carbon target measure asymmetry and determine spin precession
Asymmetry measurement

Detector signal

\[ N_{up,down} \propto 1 \pm PA \sin(2\pi \cdot f_s t) = 1 \pm PA \sin(2\pi \cdot \nu_s \cdot n_{\text{turns}}) \]

P: polarisation, A: analysing power

Asymmetry

\[ \varepsilon = \frac{N_{up} - N_{down}}{N_{up} + N_{down}} = PA \sin(2\pi \cdot \nu_s \cdot n_{\text{turns}}) \]

Challenges

• precession frequency \( f_s \approx 120 \text{ kHz} \)
• \( \nu_s \approx -0.161 \rightarrow 6 \text{ turns / precession} \)
• event rate \( \approx 5000 \text{ s}^{-1} \rightarrow 1 \text{ hit / 25 precessions} \)
  \[ \rightarrow \text{no direct fit of the rates} \]
Asymmetry measurement

COSY rf → beam revolutions: counting turn number \( n \)
detector events → assign turn number \( n \) → phase advance \( \varphi_s = 2\pi \nu_s n \)

for intervals of \( \Delta n = 10^6 \) turns: \( \varphi_s \rightarrow \varphi_s \mod 2\pi \)

scan \( \nu_s \) in some interval around \( \nu_s = \gamma G \)

true \( \nu_s \) a priori not known

\[ \sigma_{\nu_s} \lesssim 10^{-6} \]

maximum asymmetry 

\( \nu_{s,\text{max}} \)
Improvement of $\sigma_{\nu_s}$

Monitoring phase of asymmetry ($\nu_s$ fixed):

\begin{align*}
\nu_s &= \nu_{s,\text{true}} \\
\nu_s &= \nu_{s,\text{true}} + \delta\nu_s
\end{align*}

first derivative gives deviation from assumed spin tune $\nu_s$

Preliminary
Results: spin tune $\nu_s$

- spin tune $\nu_s$ can be determined to $\sigma_{\nu_s} \approx 10^{-8}$ in $\Delta t \approx 2\text{s}$
- average $\overline{\nu_s}$ in 1 cycle ($\approx 100\text{s}$) determined to $\sigma_{\nu_s} \approx 10^{-10}$
- one application: study long term stability of the ring
- future application: dedicated online feedback systems
Spin tune: probing ring imperfections

- spin tune is perturbed by small kicks $\sim a$ by ring imperfections
  $$\nu_0 = \gamma G + O(a^2)$$
- idea: probe imperfections by adding artificial imperfections
  spin kicks $\chi_1, \chi_2$ by means of e-cooler solenoids
- measure spin tune change
  $$\Delta \nu_s = \nu_s(\chi_1, \chi_2) - \nu_0$$
- expectation
  $$\Delta \nu_s \propto (y_\pm - a_\pm)^2$$
  $$y_\pm = \frac{1}{2}(\chi_1 \pm \chi_2)$$
  $$a_\pm: \text{in-plane ring imperfections}$$
Spin tune: probing ring imperfections

$\Delta v_s = 3.01072(66) \cdot 10^{-6}$
Spin tune: probing ring imperfections

spin tune map:

- parabolic behavior confirmed
- saddle point provides information on ring imperfections

Δνₛ(𝑦₋ = const)

𝑦₋ = 9.25 mrad
𝑦₋ = 3.7 mrad

further information: HK 72.2 (Fabian Trinkel), HK 72.4 (Dennis Eversmann)
Spin coherence time (SCT)

Ensemble of \( \approx 10^9 \) deuterons: coherent precession needed!

- unbunched beam: \( \frac{\Delta \gamma}{\gamma} \approx 10^{-5} \Rightarrow \text{decoherence in } < 1 \text{s} \)
- bunching: eliminate effects on \( \frac{\Delta p}{p} \) in 1st order \( \Rightarrow \tau \approx 20 \text{s} \)
- correcting higher order effects using sextupoles \( \Rightarrow \tau \approx 1000 \text{s} \)

<table>
<thead>
<tr>
<th>MXG strength [m^{-3}]</th>
<th>time [s]</th>
<th>degree of polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.48 m^{-3}</td>
<td></td>
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<td>1.05 m^{-3}</td>
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<td>1.33 m^{-3}</td>
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<tr>
<td>1.52 m^{-3}</td>
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March 24, 2015
V.Hejny, EDM at storage rings, DPG Heidelberg
SCT vs chromaticity

chromaticity: $\Delta Q_{x,y}/\Delta p$

$(Q_{x,y}: \text{betatron tunes}, p: \text{momentum})$

- also controlled by sextupoles (here: MXS, MXG)
- compare:
  - points of zero chromaticity
  - points of longest SCT

settings for zero chromaticity and longest SCT coincide!
Due to horizontal precession caused by magnetic moment:

\[ \int d \left[ \left( \vec{\beta} \times \vec{B} \right) \times \vec{S} \right] dt = 0 \]

\[ \vec{E}^* = \vec{\nu} \times \vec{B} \]

\[ \vec{s}^d = \text{50\%} \]

\[ \vec{p} \]
rf Wien filter: magnetic ring

\[ \vec{\Omega} \propto G \vec{B} + d \frac{m}{q \hbar S} (\vec{v} \times \vec{B}) \]

Due to horizontal precession caused by magnetic moment:

\[ \int d \left[ (\vec{\beta} \times \vec{B}) \times \vec{S} \right] dt = 0 \]

\[ \rightarrow \text{no net EDM effect} \]

\[ \vec{E}^* = \vec{v} \times \vec{B} \]

Use resonant “magic Wien-Filter”

\[ \vec{E}^* = \vec{E}_W + \vec{v} \times \vec{B}_W = 0 \]

- affects only magnetic moment
- introduces „EDM free“ phase advance in horizontal precession

\[ \rightarrow \text{net EDM effect can be observed} \]
rf Wien filter: design

RF B dipole
- ferrite blocks
- coil: 8 windings

RF E dipole
- foil electrodes
- distance 54 mm
- length 580 mm

\[ e \hat{E}_y \]
\[ \int \hat{F}_y \, dz \Rightarrow 0 \text{ eV/m} \]

\[ e c \beta \hat{B}_x \]
rf Wien filter: first tests in beam

Lorentz force compensation

- Amplitude and phase matching of rf E- and B-fields
- move betatron sideband onto RF frequency for max. sensitivity
- exited part of beam is removed (beam loss)
- determination of matching amplitudes and phase down to $10^{-3}$
**rf Wien filter: frequency scan**

- **Run3677** | $f_\text{Py} = 0.2896$ Hz, $\tau = 6.6399$ s
- **Run3684** | $f_\text{Py} = 0.2167$ Hz, $\tau = 4.7532$ s
- **Run3585** | $f_\text{Py} = 0.2011$ Hz, $\tau = 4.6804$ s
- **Run3574** | $f_\text{Py} = 0.2827$ Hz, $\tau = 6.7726$ s

*Vertical polarisation (asymmetry)*

- **rf on**
- **close to resonance**
- **Damping:** SCT not optimized

*Time in cycle*
Summary

• **COSY**: ideal starting point for R&D and a pre-cursor experiment
• **spin coherence time** of several hundred seconds reached
• **precise spin tune determination** tool for understand storage ring parameters (future option: phase lock for rf devices)
• new equipment: **rf Wien filter**, BPMs, deflectors, ...

Outlook

• **pre-cursor experiment** at COSY:
  proof of principle with lower sensitivity planned for < 2019
• **dedicated storage ring**:
  different options are currently under investigation
  goal: conceptual design report 2019
Jülich Electric Dipole Moment Investigations:

• ≈ 100 members:
  Aachen, Daejeon, Dubna, Ferrara, Grenoble, Indiana, Ithaca, Jülich, Krakau, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, ...

• see
  http://collaborations.fz-juelich.de/ikp/jedi