Beam and Spin Dynamics for Storage Ring Based EDM Search

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on behalf of the JEDI collaboration
(Jülich Electric Dipole Moment Investigations)
Outline

Introduction
Motivation for EDM measurements
Principle and methods

Beam and Spin Dynamics
Measurements:
- spin tune
- spin coherence time
Simulations:
- benchmarking
- investigation of systematic limits

Achievements & Goals
Electric Dipole Moments

$\vec{d}$: EDM
$\vec{\mu}$: magnetic moment
both $\parallel$ to spin

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

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

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

It is important to measure neutron and proton and deuteron, light nuclei EDMs in order to disentangle various sources of CP violation.

EDMs are candidates to solve mystery of matter-antimatter asymmetry
EDMs – Ongoing / Planned Searches

**Neutrons**
- @ILL
- @ILL,@PNPI
- @PSI
- @FRM-2
- @RCNP,@TRIUMF
- @SNS
- @J-PARC

**Molecules**
- YbF@Imperial
- PbO@Yale
- ThO@Harvard
- HfF+@JILA
- WC@UMich
- PbF@Oklahoma

**Atoms**
- Hg@UWash
- Xe@Princeton
- Xe@TokyoTech
- Xe@TUM
- Xe@Mainz
- Cs@Penn
- Cs@Texas
- Fr@RCNP/CYRIC
- Rn@TRIUMF
- Ra@ANL
- Ra@KVI
- Yb@Kyoto

**Ions-Muons**
- @BNL
- @FZJ
- @FNAL
- @JPARC

**Solids**
- GGG@Indiana
- ferroelectrics@Yale

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

P. Harris, K. Kirch … A huge worldwide effort
Spin Precession with EDM

Equation for spin motion of relativistic particles in storage rings for \( \vec{\beta} \cdot \vec{B} = \vec{\beta} \cdot \vec{E} = 0 \).

The spin precession relative to the momentum direction is given by:

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

\[
\vec{\Omega} = \frac{q}{m} \left\{ G \vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \left( \vec{v} \times \vec{E} \right) + \frac{\eta}{2} \left( \vec{E} + \vec{v} \times \vec{B} \right) \right\}.
\]

Magnetic Dipole Moment

Electric Dipole Moment

\[
G = \frac{g-2}{2}, \quad \tilde{\mu} = 2(G+1) \frac{q}{2m} \vec{S}, \text{ and } \tilde{d} = \eta \frac{q}{2m} \vec{S}.
\]
Search for Electric Dipole Moments

Approach: EDM search in time development of spin in a storage ring:

\[ \vec{\omega}_G = 0 \]
\[ \frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} \]

“Freeze“ horizontal spin precession; watch for development of a vertical component !

A *magic* storage ring for protons (electrostatic), deuterons, and helium-3

<table>
<thead>
<tr>
<th>particle</th>
<th>p (GeV/c)</th>
<th>E (MV/m)</th>
<th>B (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>0.701</td>
<td>16.789</td>
<td>0.000</td>
</tr>
<tr>
<td>deuteron</td>
<td>1.000</td>
<td>-3.983</td>
<td>0.160</td>
</tr>
<tr>
<td>(^3\text{He})</td>
<td>1.285</td>
<td>17.158</td>
<td>-0.051</td>
</tr>
</tbody>
</table>

One machine with \( r \sim 30 \text{ m} \)
Storage Ring EDM Project

… measure for development of vertical polarization

Jülich Electric Dipole Moment Investigations

Step wise:
R&D at COSY
Precursor Expt.
Lower sensitivity
Dedicated SR
Goal: $10^{-29}$ e·cm

Challenges:
Huge E-fields
Shielding B-fields
Spin coherence
Beam position
Polarimetry

> 100 members
(Aachen, Bonn, Dubna, Ferrara, Cornell, Jülich, Krakow, Michigan, St. Petersburg, Minsk, Novosibirsk, Stockholm, Tbilisi, ...)

12 PhD students from JARA-FAME (Forces and Matter Experiments)
http://collaborations.fz-juelich.de/ikp/jedi/
Inject and accelerate vertically polarized deuterons
Spin rotated with RF fields into horizontal plane
Move beam slowly (in 100 s) on internal target
Measure asymmetry and determine spin precession

At 970 MeV/c deuterons: $\gamma G \cdot f_{rev} \approx 120$ kHz

**Experimental Setup at COSY**

- RF ExB Wien filter
- RF Solenoid
- Precision Polarimeter
- Electron Cooler
- Cooler Synchrotron COSY
- Sextupole Magnets
- Polarized proton and deuteron source

**Polarized proton and deuterons**
300/600 MeV/c - 3.7 GeV/c

**Ideal starting point to investigate EDM measurements in storage rings**
Spin Tune Measurement at COSY

- EDDA Detector to measure asymmetries
- Sophisticated read-out system, which can time stamp individual event arrival times with respect to turn number: Phys. Rev. STAB 17 052803 (2014)
- Map events into first spin oscillation period
- Analyse the spin phase advance throughout the cycle

Spin tune $\nu_s$ determined to $\approx 10^{-7}$ in 2 s. 
$\bar{\nu}_s$ in cycle at $t \approx 40$ s is determined to $\approx 10^{-10}$. (submitted to PRL)
Spin coherence time at COSY

$10^9$ polarized deuterons at 970 MeV/c, bunched and electron cooled
adjust three arc sextupoles to increase spin coherence time

→ Longest SCT for transverse beam chromaticities close to zero

**Poster** by Greta Guidoboni (UNIFE, Ferrara): ID: 2811 - THPF146
Spin Coherence Time Lengthening of a Polarized Deuteron Beam with Sextupole Fields
Utilized Simulation Programs at Jülich

COSY INFINITY by M. Berz and K. Makino (MSU), MODE by S. Andrianov, A. Ivanov (StPSU):

• based on map generation using differential algebra and the subsequent calculation of the spin-orbital motion for an arbitrary particle
• including higher-order nonlinearities, normal form analysis, and symplectic tracking
• an MPI version of COSY Infinity is running on the Jülich supercomputer
• bench marking with “analog computer” Cooler Synchrotron COSY and other simulation codes
Simulations of SCT (COSY INFINITY)

- Deuterons, $p = 970\ MeV/c$, initially radial polarized
  ($\rightarrow$ precession around vertical axis)

  Chromaticity $\xi_x \approx 0$
  Chromaticity $\xi_y \approx 0$
  Parameter $\Delta \approx 0$

- Beam parameters:
  - Horizontal emittance: $\epsilon_x = 5\ mm\ mrad$
  - Vertical emittance: $\epsilon_y = 5\ mm\ mrad$
  - Momentum spread: $\left( \frac{\Delta p}{p} \right)_{rms} = 5 \cdot 10^{-4}$

No nearby spin resonances!

Courtesy: Marcel Rosenthal (FZJ)
Resonance Method in Magnetic Rings

RF $E \times B$ dipole in “Wien filter” mode
→ Avoids coherent betatron oscillations

$E^* = 0 \Rightarrow E_R = -\beta \times B_y$ „Magic RF Wien Filter“ no Lorentz force
→ Indirect EDM effect

- Modulation of horizontal spin precession in the RF Wien filter
- EDM’s interaction with the motional electric field in the rest of the ring

→ continuous buildup of vertical polarization in a horizontally polarized beam.
→ net effect due to EDM
→ Investigation of sensitivity and systematic limitations

Poster by Sebastian Mey (FZJ, Jülich): ID: 2271 - THPF031
Towards an RF Wien-Filter for EDM Experiments at COSY
Benchmarking **(COSY INFINITY)**

RF spin manipulation elements implemented. Benchmarking experiment at COSY using driven oscillations induced by the RF solenoid.

RF field: \( B_{\text{sol}} = B_0 \cos (2\pi \nu_{\text{sol}} n + \Phi_{\text{sol}}) \), **resonance condition:** \( \nu_{\text{sol}} = \gamma G \pm k \)

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**Poster** by Marcel Rosenthal (FZJ, Jülich; RWTH, Aachen): ID: 2290 - THPF032
Spin Tracking Simulations towards Electric Dipole Moment Measurements at COSY
Simulation of Resonance Method (COSY Infinity)

Uncorrected Gaussian distributed misalignments of the COSY lattice quadrupoles with a standard deviation of 0.1 mm generate a similar buildup as an EDM of \( d = 5 \cdot 10^{-19} \) e cm

Systematic EDM limit at COSY is in the order of \( d = 10^{-19} \) e·cm for a remaining orbit excitations below the millimeter level,

Poster by Marcel Rosenthal (FZJ, Jülich; RWTH, Aachen): ID: 2290 - THPF032
Spin Tracking Simulations towards Electric Dipole Moment Measurements at COSY
Simulation of Resonance Method (MODE)

Error sources:
Magnet misalignments
Wien filter:
- rotation of $10^{-4}$ rad with respect to invariant spin axis
- relative mismatch between RF Wien filter frequency and the spin resonance frequency of $10^{-5}$

$\rightarrow$ EDM in the order of $d = 10^{-19}$ e·cm

Courtesy: Stas Chekmenev (FZJ)
Simulation Program Development

Aim

- Robust and advanced numerical tracking codes for exploring various systematic effects.
- Sophisticated lattice design tools for EDM storage rings with all electrostatic as well as combined magnetic and electric elements.

Capabilities

- Accurate description of all ring elements including fringe fields.
- Allowing various error inputs for systematics investigation.
- Accurate implementation of RF spin manipulation elements.
- Calculation of orbital and spin motion with a high accuracy for over $10^9$ orbital revolutions.
- User friendly graphic interfaces for extracting physical information from tracking data.
  (e.g., orbit, betatron tune, and spin tune from tracking data)

IPAC15 satellite meeting on Spin Tracking for Precision Measurements
https://indico.cern.ch/event/368912/program
Conclusion

Achievements:

- Spin tune measurement with precision of $10^{-10}$ in a single cycle
- Long spin coherence time of up to 1000s
- Several spin tracking codes developed and benchmarked
- Investigation of systematic limit for resonance methods

Goals:

- Continue beam and spin dynamics studies at COSY (also with protons)
- First direct EDM measurement at COSY
- R&D work and design study for dedicated EDM storage ring