Spin Tracking For Polarized Beam Experiments At The JüLich Cooler Synchrotron COSY
(Juelich Electric Dipole Moment Invesigations JEDI)

December 17, 2011
Bernd Lorentz
(for the JEDI collaboration, Forschungszentrum Juelich)
Taylor Model Methods VII, Key West, USA
Topics

- Polarized beams at COSY
- Future Project srEDM
  - Motivation for EDM measurement
  - Concept of Storage Ring EDM measurements
- The Juelich EDM Investigation (JEDI)
  - SC studies (ongoing)
  - Precursor experiments (next two years)
  - JEDI magnetic/electrostatic storage ring (long term)
- Summary
The Accelerator Facility

**COoler SYnchrotron**

COSY accelerates (polarized) protons/deuterons between 300/600 and 3700 MeV/c

4 internal and 3 external experimental areas

Electron cooling at low momenta
Stochastic cooling at high momenta

Spin Tracking For Polarized Beam Experiments at COSY-Juelich
Why is COSY interesting for EDM

Ions: (pol. & unpol.): p and d

Momentum: 300/600 to 3700 MeV/c for p/d, respectively

Electron Cooling at injection
Stochastic Cooling above 1.5 GeV/c
Spin Motion

Thomas-BMT equation (Thomas [1927], Bargmann, Michel, Telegdi [1959]):

\[
\frac{d\vec{S}}{dt} = \frac{e}{\gamma m} \vec{S} \times \left[ (1 + \gamma G)\vec{B}_\perp + (1 + G)\vec{B}_\parallel \right]
\]

Precession Equation in Laboratory Frame

Number of spin rotation per turn:

\[ \nu_p = \gamma G \]

\[ G = \frac{g-2}{2}, \quad G_p = 1.7928473, \quad G_\perp = 1.800, \quad G_d = -0.142987 \]

Imperfection resonance:

\[ \gamma G = k \]

Field and positioning errors of magnets

\[ \text{Resonance strength } \sim y_{rms} \]

→ vertical orbit correction

→ adiabatic spin flip (partial snake)

Intrinsic resonance:

\[ \gamma G = (kP \pm Q_y) \]

P: super-periodicity

Q_y: vertical tune

Vertical focusing fields

Resonance strength \( \sim \sqrt{\epsilon_y} \)

→ vertical tune jumps

→ vertical coherent betatron oscillations
Spin Resonances

### Protons

<table>
<thead>
<tr>
<th>Momentum (GeV/c)</th>
<th>Kinetic energy (GeV)</th>
<th>Imperfection resonance $\gamma \cdot G = \ldots$</th>
<th>Intrinsic resonance $\gamma \cdot G = \ldots \pm Q_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.464</td>
<td>0.108</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>0.835</td>
<td>0.318</td>
<td>6-</td>
<td></td>
</tr>
<tr>
<td>0.986</td>
<td>0.422</td>
<td>-1+</td>
<td></td>
</tr>
<tr>
<td>1.259</td>
<td>0.632</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>1.512</td>
<td>0.841</td>
<td>7-</td>
<td></td>
</tr>
<tr>
<td>1.634</td>
<td>0.946</td>
<td>0+</td>
<td></td>
</tr>
<tr>
<td>1.871</td>
<td>1.155</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>2.103</td>
<td>1.364</td>
<td>8-</td>
<td></td>
</tr>
<tr>
<td>2.217</td>
<td>1.469</td>
<td>1+</td>
<td></td>
</tr>
<tr>
<td>2.443</td>
<td>1.678</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>2.666</td>
<td>1.888</td>
<td>9-</td>
<td></td>
</tr>
<tr>
<td>2.776</td>
<td>1.992</td>
<td>2+</td>
<td></td>
</tr>
<tr>
<td>2.997</td>
<td>2.202</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>3.215</td>
<td>2.411</td>
<td>10-</td>
<td></td>
</tr>
<tr>
<td>3.324</td>
<td>2.516</td>
<td>3+</td>
<td></td>
</tr>
</tbody>
</table>

### Deuterons

Graph showing depolarizing resonances for deuterons with operation range.

$Q_y = 3.60$
Polarized Proton Beam

Methods to preserve polarization

→ tune jumps
→ vertical orbit excitation

Polarization during acceleration

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EDDA Polarimeter

- Two-layered cylindrical scintillator structure
  - Outer Layer (→ trigger!)
    - D: 32 overlapping slabs of triangular cross-section
      \( \Delta \phi = 11.25^\circ \)
    - F,R: 2x29 semirings \( \Delta \theta_{\text{lab}} = 2.5^\circ \)
      - Left semirings \( \phi \in [-90^\circ, 90^\circ] \)
      - Right semirings \( \phi \in [90^\circ, 270^\circ] \)

Proton Polarimetry: Kinematic and Coplanar Coincidences (pp elastic). Left-Right Asymmetries by selection on Halfrings => \( P_V \).
Deuteron Polarimetry for dEDM:
Coincidence Halfrings and groups of bars:
Left/Right/Top/Bottom Asymmetries => \( P_V, P_T \)
Highlight from recent polarized beam experiments

P.Goslawski et al., High precision beam momentum determination in a synchrotron using a spin-resonance method.
Physical Review Special Topics - Accelerators and Beams (Vol.13, No.2) Feb. 2010

$\eta$-mass determination in $d\,p \rightarrow ^3$He $\eta$ at Anke
Use depolarizing resonance for accurate determination of beam momentum
$f_{\text{res}} = (1 + \gamma G) f_0$

$f_0$ from Schottky Spectra
$f_{\text{res}}$ from depolarization (measured with EDDA)

Result: $\Delta p/p < 6 \times 10^{-5}$ at 13 momenta between 3100 and 3200 MeV/c
Conclusion from COSY experience

Polarized Proton and Deuteron Operation well under control
(no spin tracking needed for this so far)

All tools needed for detailed experimental studies of polarized beam behaviour are available at COSY-Juelich

THE spin-physics machine for hadron physics
THE ideal test facility for the future srEDM measurements

The polarimetry group of the BNL srEDM collaboration is running tests at COSY in close collaboration with COSY staff since 2008 (LOI 2004) (E.Stevenon)

Recently, at COSY the potential for a dedicated srEDM Experiment is pursued by the just forming JEDI collaboration
Electric Dipole Moments (EDMs)

Permanent EDMs violate parity $P$ and time reversal symmetry $T$.
Assuming CPT to hold, combined symmetry $CP$ violated as well.

EDMs are candidates to solve mystery of matter-antimatter asymmetry → may explain why we are here!
History of neutron EDM limits

- Smith, Purcell, Ramsey
  PR 108, 120 (1957)
- RAL-Sussex-ILL
  \( d_n < 2.9 \times 10^{-26} \text{ e.cm} \)
  PRL 97, 131801 (2006)

Electro-weak standard model expectation: \( \sim 10^{-32} \text{ e.cm} \)

Adopted from K. Kirch
**Limits for Electric Dipole Moments**

**EDM searches - only upper limits up to now (in e·cm):**

<table>
<thead>
<tr>
<th>Particle/Atom</th>
<th>Current EDM Limit</th>
<th>Future Goal</th>
<th>$\sim d_n$ equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>$&lt; 3 \times 10^{-26}$</td>
<td>$\sim 10^{-28}$</td>
<td>$10^{-28}$</td>
</tr>
<tr>
<td>$^{199}$Hg</td>
<td>$&lt; 3.1 \times 10^{-29}$</td>
<td>$\sim 10^{-29}$</td>
<td>$10^{-26}$</td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>$&lt; 6 \times 10^{-27}$</td>
<td>$\sim 10^{-30} - 10^{-33}$</td>
<td>$\sim 10^{-26} - 10^{-29}$</td>
</tr>
<tr>
<td>Proton</td>
<td>$&lt; 7.9 \times 10^{-25}$</td>
<td>$\sim 10^{-29}$</td>
<td>$10^{-29}$</td>
</tr>
<tr>
<td>Deuteron</td>
<td>?</td>
<td>$\sim 10^{-29}$</td>
<td>$3 \times 10^{-29} - 5 \times 10^{-33}$</td>
</tr>
</tbody>
</table>

Huge efforts underway to improve limits / find EDMs

Sensitivity to **NEW PHYSICS** beyond the Standard Model

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**485. WE-Heraeus-Seminar** (July 04–06, 2011)

Search for Electric Dipole Moments (EDMs) at Storage Rings

http://www2.fz-juelich.de/ikp/edm/en/
NEW: 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!
The frozen spin Method

For transverse electric and magnetic fields in a ring \((\vec{\beta} \cdot \vec{B} = \vec{\beta} \cdot \vec{E} = 0)\), anomalous spin precession is described by

\[
\tilde{\omega}_G = -\frac{q}{m} \left\{ G \vec{X} \vec{B} + \left[ G - \left( \frac{m}{p} \right)^2 \right] \frac{\vec{\beta} \times \vec{E}}{c} \right\} \quad \left( G = \frac{g-2}{2} \right)
\]

Magic condition: Spin along momentum vector

1. For any sign of G, in a combined electric and magnetic machine

\[
E = \frac{GBc\beta\gamma^2}{1-G\beta^2\gamma^2} \approx GBc\beta\gamma^2
\]

2. For G>0 (protons) in an all electric ring

\[
G - \left( \frac{m}{p} \right)^2 = 0 \rightarrow p = \frac{m}{\sqrt{G}} = 700.74 \ \text{MeV} \cdot c \quad \text{(magic)}
\]
Magic condition: Protons

E-field only

Proton EDM

radius (m)

E

E-field (MV/m)
Magic condition: Deuterons

E and B fields

Deuteron EDM

radius (m)

kinetic energy (MeV)

B=0.1 T
B=0.2 T
B=0.3 T

radial E-field (MV/m)

Deuteron EDM

kinetic energy (MeV)

B=0.1 T
B=0.2 T
B=0.3 T

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Magic condition: Helions

E and B fields

Helion EDM

radius (m)

kinetic energy (MeV)

Helion EDM

radial E-field (MV/m)

kinetic energy (MeV)
NEW: 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, …

<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 ~ 30 m
Two storage ring projects being pursued

BNL for protons all electric machine

Jülich, focus on deuterons, or a combined machine

CW and CCW propagating beams

(from R. Talman)

(from A. Lehrach)
### International srEDM Network

#### Institutional (MoU) and Personal (Spokespersons …) Cooperation, Coordination

<table>
<thead>
<tr>
<th>srEDM Collaboration (BNL)</th>
<th>srEDM Collaboration (FZJ)</th>
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</table>

#### Common R&D

- **RHIC**
  - Beam Position Monitors
  - (…)

- **EDM-at-COSY**
  - Polarimetry
  - Spin Coherence Time
  - Cooling
  - (…)

- **Spin Tracking**

#### Study Group

- **DOE-Proposal**
- **Precursor; Ring Design**
- **CD0, 1, …**
- **HGF Application(s)**

#### pEDM Ring at BNL

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Spin Tracking For Polarized Beam Experiments at COSY-Juelich
Why do we need longterm spintracking calculations, now

Spin closed orbit

one particle with magnetic moment makes one turn

\[ \hat{n}_{CO} \]

“spin closed orbit vector”

stable polarization if \( \vec{S} \parallel \hat{n}_{CO} \)

And that’s all we needed to run the hadron physics experiments of interest

Adopted from H.O. Meyer

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Spin coherence

We usually don’t worry about coherence of spins along $\hat{n}_{CO}$.

At injection all spin vectors aligned (coherent)

After some time, spin vectors get out of phase and fully populate the cone.

Polarization not affected!

Situation very different, when you deal with $\vec{S} \perp \hat{n}_{CO}$.

At injection all spin vectors aligned

After some time, the spin vectors are all out of phase and in the horizontal plane.

Longitudinal polarization vanishes!

In an Edm machine with frozen spin, observation time is limited.
Estimate of spin coherence times (Kolya Nikolaev)

One source of spin coherence are random variations of the spin tune due to the momentum spread in the beam

$$\delta \theta = G \delta \gamma \quad \text{and} \quad \delta \gamma \quad \text{is randomized by e.g., electron cooling}$$

$$\cos(\omega t) \Rightarrow \cos(\omega t + \delta \theta)$$

$$\tau_{sc} \approx \frac{1}{f_{rev} G^2 \langle \delta \gamma^2 \rangle} \approx \frac{1}{f_{rev} G^2 \gamma^2 v^4 \left\langle \left( \frac{\delta p}{p} \right)^2 \right\rangle^{-1}}$$

**Estimate:**

$$T_{kin} = 100 \text{ MeV} \quad f_{rev} = 0.5 \text{ MHz}$$

$$G_p = 1.79 \quad G_d = -0.14$$

$$\tau_{sc}(p) \approx 3 \times 10^3 \text{ s} \quad \tau_{sc}(d) \approx 5 \times 10^5 \text{ s}$$

Spin coherence time for deuterons may be \(\sim 100\) larger than for protons
First measurement of spin coherence time

Test measurements at COSY

Polarimetry:

Spin coherence time:

5 s  25 s  5 s

decoherence time  oscillation capture

from E. Stephenson
(BNL polarimetry group)
Precursor Experiment in COSY:
Resonance Method with RF E-fields

spin precession governed by:
\[
\frac{d\vec{S}}{dt^*} = \vec{d} \times \vec{E}^* + \vec{\mu} \times \vec{B}^*
\]
(* rest frame)

Two situations:
1. \( B^* = 0 \Rightarrow B_y = \beta \times E_R \) (= 70 G for \( E_R = 30 \text{ kV/cm} \))
   EDM effect
2. \( E^* = 0 \Rightarrow E_R = -\beta \times B_y \)
   no EDM effect

This way, the Edm signal gets **accumulated** during the cycle.
Brings us in the \( 10^{-24} \text{ e} \cdot \text{cm} \) range for \( d_d \)

\[ P_y \text{ drops} \quad \sqrt{P_x^2 + P_z^2} \text{ grows} \]
PE 2: Simulation of resonance Method with RF E-fields and deuterons at COSY

Parameters:
- beam energy: $T_d = 50$ MeV
- assumed EDM: $d_d = 10^{-20} \text{ e}\cdot\text{cm}$
- E-field: 10 kV/cm

Constant E-field

E-field reversed every $-\pi/(G\cdot\gamma) \sim 21$ turns

Number of turns

b.lorentz@fz-juelich.de Spin Tracking For Polarized Beam Experiments at COSY-Juelich
PE 2: Simulation of resonance Method with RF E-fields and deuterons at COSY

Parameters:
- beam energy \( T_d = 50 \) MeV
- assumed EDM \( d_d = 10^{-20} \) e\( \cdot \)cm
- E-field 10 kV/cm

Linear extrapolation of \( P = \sqrt{P_x^2 + P_z^2} \) for a time period of \( \tau_{sc} = 1000 \) s (=3.7\( \cdot \)10^8 turns)

EDM effect accumulates

Polarimeter determines \( P_x, P_y \) and \( P_z \)
Status of the Spin Tracking Calculations

The shown results for explanation of measured data and for predictions for the precursor experiments use a so-called ‘no lattice‘ model, i.e. only the precession of the spin in the bending fields is considered. (no betatron oscillation, no higher order fields, no fringe fields…)

This obviously is not sufficient for a high precision experiment as envisioned, a long term tracking code with polarization is urgently needed, COSY-INFINITY was identified as good candidate

We started to use COSY-INFINITY earlier this year, but we are at the very beginning
People working on this

PD Dr. A. Lehrach, Dr. B. Lorentz, A. Peece
• Modelling of Polarization in COSY
• Comparison of Model and Experiment
• Modelling Precursor Experiments

Prof. Dr. Yuri Senichev, D. Zyuzin,
• Multi Processor Installation of the code in Juelich
• Design of a pure electrostatic lattice (p-EDM)
• Fringe field effects in electrostatic ring (Cooperation with Prof. S. Andrianoz, A. Ivanov of St. Petersburg SU)

We need to work in close cooperation with M. Berz
Spin Tracking through the COSY lattice

Qualitative Check of Intrinsic Resonances

19 rays, with horizontal, vertical and momentum offsets

\[ P_y = \text{average vertical polarization over all turns and rays} \]
Spin Tracking through the COSY lattice

Qualitative Check of Intrinsic Resonances

9 rays, with vertical and momentum offsets

Py = average vertical polarization over all turns and rays
Spin Tracking through the COSY lattice

Qualitative Check of Imperfection Resonances

momentum offsets

\[ P_y = \text{average vertical polarization over all turns and rays} \]
Spin Tracking through the COSY lattice

Qualitative Check of Imperfection Resonances

horizontal offsets

\[ Py = \text{average vertical polarization over all turns and rays} \]
Spin Tracking through the COSY lattice

Qualitative Check of Imperfection Resonances
vertical offsets

\[ Py = \text{average vertical polarization over all turns and rays} \]
Spin Tracking through the COSY lattice

Qualitative Check of Imperfection Resonances
vertical and horizontal offsets

Py = average vertical polarization over all turns and rays
Spin Tracking through the COSY lattice

Qualitative Check of Imperfection Resonances
vertical, horizontal and momentum offsets

Py = average vertical polarization over all turns and rays
Spin Tracking through the COSY lattice

Qualitative Check of Imperfection Resonances
vertical, horizontal and momentum offsets

All that was shown is only qualitative, to learn how to use
COSY Infinity with Juelich COSY lattice,
I think I know what I am doing
Quanititative investigations need to follow
(we could even think to compare to measurements)
Spin Tracking through the COSY lattice

Next steps:

We could (and probably will) go in a more quantitative investigation of the started spin tracking calculations.

But more important: introduce „spin flipper“ element in COSY-Infinity Tracking

• spin coherence time measurements (ongoing) use rf solenoid magnet
• precursor experiment will use rf electrostatic element
  Both of these elements are run as „spin flipper“ on the frequency of the spin precession, not on the revolution frequency
  \[ f_{\text{flipper}} = f_{\text{rev}} \times (k + \gamma G) \]

Therefore the OTM tracking method of COSY-Infinity needs to be extended (discussion with M. Berz are ongoing)
srEDM cooperations

International srEDM Network

Institutional (MoU) and Personal (Spokespersons …) Cooperation, Coordination

srEDM Collaboration (BNL)  srEDM Collaboration (FZJ)

Common R&D

RHIC
Beam Position Monitors
(…)

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Polarimetry
Spin Coherence Time
Cooling
(…)

Spin Tracking

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DOE-Proposal

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CD0, 1, …

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pEDM Ring at BNL  JEDI

b.lorentz@fz-juelich.de  Spin Tracking For Polarized Beam Experiments at COSY-Juelich
EDM Workshop at ECT* (Trento)

October 1-5, 2012

Organizing committee

- Jülich
  Hans Ströher h.stroeher@fz-juelich.de
  Frank Rathmann f.rathmann@fz-juelich.de
  Andreas Wirzba a.wirzba@fz-juelich.de

- Brookhaven
  Mei Bai mbai@bnl.gov
  William Marciano marciano@bnl.gov
  Yannis Semertzidis yannis@bnl.gov
• Measurement of EDMs extremely difficult, but the physics is fantastic!

• **COSY** is a perfect test facility, spin coherence time measurements and comparison to model expectations will come soon

• Systematic error estimates for all precursor experiment require reliable spin tracking tools, e.g. COSY-INFINITY. **Top priority to make them available ASAP!**

• New collaboration „JEDI“ being formed
Lower limit on electron-cooled SCT from January run

RF-solenoid produces small polarization kicks about longitudinal direction. (Kicks vary as cosine with maximum $< 4 \mu\text{rad}$.)
On $(1-G\gamma)$ resonance, this produces continuously reversing vertical $P_Y$.

Set process to turn RF-solenoid ON, OFF, then ON again.

During this time the polarization is in the ring plane and free to decohere.
If oscillation returns, (1) beam is still polarized, and (2) the RF-solenoid was still in phase (thus this is a lower limit).

Lines added to guide the eye.

reference oscillation  5 s  decoherence time  25 s  oscillation capture  5 s

b.lorentz@fz-juelich.de  Spin Tracking For Polarized Beam Experiments at COSY-Juelich
3 ON-OFF-ON runs had usable data.

Distribution of synchrotron amplitudes

Cooled

Uncooled