Perspectives for Storage Ring EDM Searches

October 2, 2012 | Andreas Lehrach

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

Introduction

EDM Measurements in Storage Rings
  COSY as EDM Injector
  Dedicated Storage Rings
  First Direct Measurement at COSY

Simulation Programs
  Computational Needs
  Performance and Benchmarking

Summary/Outlook
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>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>&lt; 3 \times 10^{-26}</td>
<td>~10^{-28}</td>
</tr>
<tr>
<td>$^{199}$Hg</td>
<td>&lt; 3.1 \times 10^{-29}</td>
<td>~10^{-29}</td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>&lt; 6 \times 10^{-27}</td>
<td>~10^{-30} – 10^{-33}</td>
</tr>
<tr>
<td>Proton</td>
<td>&lt; 7.9 \times 10^{-25}</td>
<td>~10^{-29}</td>
</tr>
<tr>
<td>Deuteron</td>
<td>?</td>
<td>~10^{-29}</td>
</tr>
</tbody>
</table>

Huge efforts underway to improve limits / find EDMs

CP can have different sources

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

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:

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

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

Magnetic Moment

Electric Dipole Moment

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

NEW approach: EDM search in time development of spin in a storage ring:

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

“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)He</td>
<td>1.285</td>
<td>17.158</td>
<td>-0.051</td>
</tr>
</tbody>
</table>

One machine with \( r \sim 30 \text{ m} \)

Systematic error due to vertical electric fields and horizontal magnetic fields
Ions: (pol. & unpol.) p and d

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

Circumference of the ring: 184 m

Electron Cooling at injection

Stochastic Cooling above 1.5 GeV/c

Injection into EDM ring:
Longitudinal polarized, pre-cooled beam single bunch or bunch into bucket injection
COSY Beam Parameter

- Beam intensity (polarized beams):
  \(10^{10}\) protons or deuterons

- Beam polarization (1 GeV/c):
  0.8 of maximum possible value

- Transverse emittances:
  15-30 \(\pi\) mm mrad (geom., 3\(\sigma\) uncooled at injection)
  below 3 \(\pi\) mm mrad (geom., 3\(\sigma\) cooled at injection)

- Momentum spread:
  \((\Delta p/p)_{\text{rms}} < 10^{-3}\) (uncooled)
  \(< 10^{-4}\) (cooled)
New 2 MV Electron Cooler at COSY

- Energy Range: 0.025 ... 2 MeV
- High Voltage Stability: < $10^{-4}$
- Electron Current: 0.1 ... 3 A
- Electron Beam Diameter: 10 ... 30 mm
- Cooling section length: 2.694 m
- Magnetic field (cooling section): 0.5 ... 2 kG

Installation at COSY in the winter shutdown 2012/13
Siberian Snakes

Spin manipulation or snake fields:
- longitudinal fields (solenoids) at lower energies
- transverse fields (helical dipoles) at higher energies

Full Siberian snake for 1 GeV/c: 3.75 Tm (protons), 12.24 Tm (Deuterons)

Superconducting 4.7 Tm solenoid is ordered.
- Overall length: 1 m
- Ramping time 30 s

Installation at COSY in spring 2013
Deuteron EDM Proposal

Deuteron momentum: $p = 1$ GeV/c,
Ring parameter: $R_B = 8.4$ m, $<R> \sim 10$ m, $C = 85$m
Deflectors: $E_R = -12$ MV/m (radial), $B_V = 0.48$ T (vertical)

- 2004 BNL proposal: single ring
  CW and CCW consecutive beam injections
  Limiting error: time-dependent part of the average vertical electric field over the entire ring
  $\rightarrow$ sensitivity $\sim 10^{-27}$ e · cm for one year measurement

- 2008 BNL proposal: double ring
  CW and CCW simultaneously
  2-in-1 magnet design with common E-field plates
  $\rightarrow$ sensitivity $\sim 10^{-29}$ e · cm for one year measurement

See http://www.bnl.gov/edm
Figure 1: “All-In-One” lattice for measuring EDM’s of protons, deuterons, and helions.
Jülich All-In-One Ring Lattice

Iron-free, current-only, magnetic bending, eliminates hysteresis
→ achievable field of copper magnets of ~ 0.15 T.

Talk by R. Gebel
# EDM Projects

## Proton EDM
- **BNL**

## Light-Ion EDM
- **Jülich**

### R&D Activity

<table>
<thead>
<tr>
<th>Activity</th>
<th>Goal</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal Polarimeter</td>
<td>spin as a function of time</td>
<td>EDM at COSY</td>
</tr>
<tr>
<td></td>
<td>Systematic errors &lt; 1 ppm</td>
<td>EDM at COSY</td>
</tr>
<tr>
<td></td>
<td>Full-scale polarimeter</td>
<td>EDM at COSY</td>
</tr>
<tr>
<td>Spin Coherence Time</td>
<td>&gt;10^3 s</td>
<td>EDM at COSY</td>
</tr>
<tr>
<td>Beam Position Monitor</td>
<td>resolution 10 nm, 1 Hz BW</td>
<td>BNL</td>
</tr>
<tr>
<td></td>
<td>64 BPMs, 10^7 s measurement time</td>
<td>RHIC IP</td>
</tr>
<tr>
<td></td>
<td>→ 1 pm (stat.) relative position (CW-CCW)</td>
<td></td>
</tr>
<tr>
<td>E/B-field Deflector</td>
<td>17 MV/m 2 cm plate separation, 0.15-0.5T</td>
<td>Jülich</td>
</tr>
</tbody>
</table>
Spin Manipulation at COSY

RF-induced spin resonance:

\[ f_r = f_c (k \pm \gamma G) \]

RF Dipole (dismantled)
- 8-turn water-cooled copper coil in a ferrite box
- Length 0.6 m
- Frequency range roughly 0.4 to 1.2 MHz
- Integrated field \( \int B_{\text{rms}} \, dl \approx 0.54 \, \text{T} \cdot \text{mm} \)

RF Solenoid
- Water-cooled copper coil in a ferrite box,
- Length 0.6 m
- Frequency range roughly 0.6 to 1.2 MHz
- Integrated field \( \int B_{\text{rms}} \, dl \approx 1 \, \text{T} \cdot \text{mm} \)
Resonance Strength

RF Solenoid

\[ \mathcal{E}_{Bdl} = \frac{1}{\pi 2 \sqrt{2}} \frac{e(1 + G)}{p} \int B_{rms} dl, \]

RF Dipole

\[ \mathcal{E}_{Bdl} = \frac{1}{\pi 2} \frac{e(1 + G\gamma)}{p} \int B_{rms} dl, \]

\[ \frac{\mathcal{E}_{FS}}{\mathcal{E}_{Bdl}} = A + \frac{B}{|\nu_y - \nu_r|}. \]

SPIN@COSY Collaboration

Resonance Method with RF E/B Fields

First direct measurement in COSY developed by the Jülich study group

RF-E/B spin flipper to observe a spin rotation by the EDM

Two possibilities:

1. $B^* = 0 \Rightarrow B_Y = \beta \times E_R$ (~70 G for $E_R = 30$ kV/cm)  
   "Direct" EDM effect

2. $E^* = 0 \Rightarrow E_R = -\beta \times B_Y$  
   "Magic RF Wienfilter"  
   No-Lorenz Force,  
   "Indirect" EDM effect

Tilt of the precession plane due to EDM

Observable:
Accumulation of spin rotations within spin coherence time

- EDM signal is **increased** during the cycle
- Statistical sensitivity for $d_d$ in the $10^{-23}$ to $10^{-24}$ e·cm range possible
- Alignment and field stability of ring magnets
- Imperfection of RF E(B) spin flipper?

Talk by F. Rathmann
RF E/B Spin Flipper

Two steps to develop a RF E/B Spin Flipper

1) Low-power device:
   E-Field : << 1 MV/m, B-Field ~ 7 Gauss

2) High-power device:
   E-Field : >> 1 MV/m, B-Field ~ 70 Gauss

Two resonance circuits with common master clock
Length ~1m
Frequency 0.3-1 MHz
In vacuum ~$10^{-9}$ mbar

or microwave structure (strip line)
1. Studies of the spin coherence time (SCT) with horizontal/vertical RF-B/E spin flipper
   - Different wave forms at different spin harmonics and beam energies
   - Goal is to get optimum setting of the RF-B field for maximum spin coherence time

2. Investigation of systematic effect with vertical/horizontal RF-B/E spin flipper
   - Alignment and field quality RF-B flipper
   - Opening angle of spin ensemble (beam cooling and heating)
   - Alignment of the ring magnets

3. Development and benchmark precision simulation programs for spin dynamics in storage ring
   - COSY-Infinity, integrating code, simple code

4. Polarimetry

5. Development of a high-power RF-E(B) spin flipper
Spin Coherence Time with RF Flipper

Exciting result of the Jülich Study Group

\[ f_r = f_c (k \pm \gamma G) \]

\[ \frac{1}{\tau_T} = \frac{1}{\tau_{FP}} + \frac{1}{\tau_{RF}} - A_{FP, RF} \cdot f(\tau_{FP}, \tau_{RF}) \]

• Possibility to increase spin coherence time by 3 to 5 orders of magnitude in the ideal case
COSY Upgrade

1. Improved closed-orbit control system for orbit correction in the micrometer range
   → Increasing the stability of correction-dipole power supplies
   → Increase number of correction dipoles and beam-position monitors (BPMs)
   → Improve BPM accuracy, limited by electronic offset and amplifier linearity
   → Systematic errors of the orbit measurement (e.g., temperature drift)

2. Alignment of Magnets and BPMs
   → More precise alignment of the quadrupole and sextupole magnets
   → BPMs have to be aligned with respect to the magnetic axis of these magnets

3. Beam oscillations
   → Excited by vibrations of magnetic fields induced by the jitter of power supplies
   → Coherent beam oscillation

4. Longitudinal and transverse wake fields
   → Ring impedances
## Overall Schedule

### Stepwise Approach of the JEDI Project

<table>
<thead>
<tr>
<th>Step</th>
<th>Aim / scientific goal</th>
<th>Device / Tools</th>
<th>Storage ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Spin coherence time studies</td>
<td>Horizontal/vertical RF-B/E spin flipper</td>
<td>COSY</td>
</tr>
<tr>
<td></td>
<td>Systematic error studies</td>
<td>Vertical/horizontal RF-B/E spin flipper</td>
<td>COSY</td>
</tr>
<tr>
<td>2</td>
<td>COSY upgrade</td>
<td>Orbit control, magnets, ...</td>
<td>COSY</td>
</tr>
<tr>
<td></td>
<td>First direct EDM measurement at $10^{-24}$ e·cm</td>
<td>High-power RF-E/B spin flipper</td>
<td>Modified COSY</td>
</tr>
<tr>
<td>3</td>
<td>Built a dedicated all-in-one ring for p, d, $^3$He</td>
<td>Common magnetic-electrostatic deflectors R&amp;D funded by ARD (Accelerator Research and Development) of HGF</td>
<td>Dedicated ring</td>
</tr>
<tr>
<td>4</td>
<td>EDM measurement for p, d, $^3$He at $10^{-29}$ e·cm</td>
<td></td>
<td>Dedicated ring</td>
</tr>
</tbody>
</table>

**Time scale**

- Step 1-2: > five years
- Step 3-4: > five years
Computational Needs

- Particle revolutions: $\gg 10^6$ turns (1 seconds)
  $\rightarrow$ efficient simulation program

- Number of particle: $10^6$
  $\rightarrow$ MPI version on a supercomputer

- Precision:
  - COSY measurement: $10^{-13} - 10^{-12}$ radians per turn
  - Dedicated ring: EDM rotation with by of $10^{-15}$ radians per turn
    $\rightarrow$ roughly $10^{-18}$ radians per element
  $\rightarrow$ double precision (64 Bit) provides 16 significant decimal digits precision

- EDM spin kick is required

- RF E/B spin flipper element is needed
Utilized Simulation Programs

COSY Infinity:

- 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
- the upgrade of COSY Infinity is supervised by M. Berz

- an MPI version of COSY Infinity is already running on the computer cluster at Michigan State University
- a project for the Jülich supercomputer is starting end of this year
Code Performance

- Scalability testing JUGENE (IBM BlueGene/P) with 73728 nodes (294912 cores)
- Peak performance: 1 Petaflops/sec
- 32768 particles tracked for 10^6 turns (test account)

<table>
<thead>
<tr>
<th>#cores</th>
<th>Absolute timing (s)</th>
<th>Speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>24387</td>
<td>1.0</td>
</tr>
<tr>
<td>16</td>
<td>12187</td>
<td>2.0</td>
</tr>
<tr>
<td>32</td>
<td>6140</td>
<td>3.97</td>
</tr>
<tr>
<td>64</td>
<td>3067</td>
<td>7.95</td>
</tr>
</tbody>
</table>

Code Performance

Scaling behavior of COSY-INFINITY. This test was performed with 3rd order of nonlinearities, absolute timings per time step (s) and relative speedup normalized 8 cores are given.

Courtesy: D. Zyuzin (FZJ)
Benchmarkedring

Integrating program:
• differential equations of particle and spin motion in electric and magnetic fields are solved using Runge-Kutta integration (integration step size 0.5 ps → maximum tracking 10 ms)

Numerical integration:
• numerical integration of the Thomas-BMT differential equations for a spin motion with smoothly approximated parameters of orbital motion

Rotation matrices:
• matrices for dipoles and RF Spin flipper including synchrotron oscillation

Experiments:
• “analog computer” Cooler Synchotron COSY

Talk by Y. Senichev
EDM Measurement: Stepwise approach of the JEDI Project

- R&D work at COSY together with BNL
- Upgrade and first direct measurement at COSY
- Upgrade COSY as EDM injector
- Build a dedicated storage ring

Computational Needs

- Efficient simulation program on a super computer
- Benchmarking with other simulation programs and COSY experiments