PROJECT OVERVIEW AND COMPUTATIONAL NEEDS
TO MEASURE EDMs AT STORAGE RINGS

August 20, 2012  |  Andreas Lehrach

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

Introduction
  Motivation and History of EDM Measurements

EDM Measurements in Storage Rings
  Principle and Methods
  Dedicated Storage Rings
  First Direct Measurement at COSY

Simulation Programs
  Computational Needs
  Utilized Simulation Programs
  Performance and Benchmarking

Summary/Outlook
Electric Dipole Moments: What is it?

EDM: Permanent spatial separation of positive an negative charges

- Water molecule: $d = 2 \cdot 10^{-9} \text{ e}\cdot\text{cm}$

- Water molecule can have large electric dipole moment because ground state has two degenerate states of different parity

- This is not the case for proton.
- Here the existence of a permanent EDM requires both T and P violation, i.e. assuming CPT invariance this implies CP violation.
Electric Dipole Moments

CP can have different sources:

• Weak Interaction (unobservable small)

• QCD $\theta$ term (limit set by neutron EDM measurement) — Part of Standard Model —

• Sources beyond SM

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
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)

More than 50 years of effort

Electro-weak standard model expectation: \(~10^{-32} \text{ e cm}\)
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 ×10⁻²⁶</td>
<td>~10⁻²⁸</td>
</tr>
<tr>
<td>¹⁹⁹Hg</td>
<td>&lt; 3.1 ×10⁻²⁹</td>
<td>~10⁻²⁹</td>
</tr>
<tr>
<td>¹²⁹Xe</td>
<td>&lt; 6 ×10⁻²⁷</td>
<td>~10⁻³⁰ – 10⁻³³</td>
</tr>
<tr>
<td>Proton</td>
<td>&lt; 7.9 ×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

Sensitivity to NEW PHYSICS beyond the Standard Model

EDM workshop at ECT* Trento, Italy
October 1 - 5, 2012
„EDM Searches at Storage Rings“
http://www.ectstar.eu/
Spin Precession

Spin precession for particles at rest in electric and magnetic fields:

\[ \frac{d\vec{S}^*}{dt^*} = \vec{d} \times \vec{E}^* + \vec{\mu} \times \vec{B}^* \]

(* rest frame)

In a real neutral particle EDM experiment for non-relativistic particles, the spin precession is given by:

\[ \frac{d\vec{S}^*}{dt^*} = \vec{d} \times (\vec{E} + \vec{v} \times \vec{B}) + \vec{\mu} \times (\vec{B} - \vec{v} \times \vec{E}) \]

Ideal vertical B-Fields and horizontal E-Fields:

EDM signal

Systematic error

Equation for spin motion of relativistic particles in storage rings more complicated
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:

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

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

Magnetic Moment

Electric Dipole Moment

\[
G = \frac{g - 2}{2}, \quad \bar{\mu} = 2(G + 1) \frac{e\hbar}{2mc} \vec{S}, \quad \text{and} \quad \bar{d} = \eta \frac{e\hbar}{2mc} \vec{S}.
\]
Frozen Spin Method (FSM)

Spin vector

Momentum vector

Lower energy particle

...just right

Higher energy particle

Spin coherence time: $10^3$ s for measurement on $10^{-29}$ e·cm level

For $\beta \cdot B = \beta \cdot E = 0$, the spin precession (magnetic moment) relative to the momentum direction is given by

$$\vec{\omega}_G = \frac{e}{m} \left[ G \cdot \vec{B} + \left( \frac{1}{\gamma^2 - 1} - G \right) \frac{\vec{\beta} \times \vec{E}}{c} \right], \quad G = \frac{g - 2}{2}$$
Freezing Spin Precession with E-Fields

\[ \frac{1}{\gamma^2 - 1} - G = 0 \rightarrow \gamma = \sqrt{\frac{1}{G} + 1} \]

\[ \rightarrow G > 0, \text{ if only electric fields are applied} \]

\[ \gamma = \sqrt{\frac{1}{G} + 1} \iff p = \frac{m}{\sqrt{G}} \]

\[ \mu_p / \mu_N = 2.792\,847\,356 \ (23) \rightarrow G_p = 1.7928473565 \]
\[ \mu_d / \mu_N = 0.857\,438\,2308 \ (72) \rightarrow G_d = -0.14298727202 \]
\[ \mu_{He-3} / \mu_N = -2.127\,497\,718 \ (25) \rightarrow G_{3He} = -4.1839627399 \]

Nuclear magneton: \[ \mu_N = e\hbar / (2m_p c) = 5.050\,783\,24 \ (13) \cdot 10^{-27} \ J \ T^{-1} \]

\[ \rightarrow \text{Magic momentum for protons: } p = 700.74 \ MeV/c \]
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\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}
Statistical Sensitivity of an EDM Experiment

\[ \sigma_{dp} \approx \frac{3\hbar}{PAE_R \sqrt{N_{Beam} f T_{Tot} \tau_{Spin}}} \]

- \( P = 0.8 \) Beam polarization
- \( A = 0.6 \) Analyzing power of polarimeter
- \( E_R = 17 \text{ MV/m} \) Radial electric field strength
- \( N_{Beam} = 2 \cdot 10^{10} \text{ p/fill} \) Total number of stored particles per fill
- \( f = 0.55\% \) Useful event rate fraction (polarimeter efficiency)
- \( T_{Tot} = 10^7 \text{ s} \) Total running time per year
- \( \tau_{Spin} = 10^3 \text{ s} \) Polarization lifetime (Spin Coherence Time)

\[ \sigma \approx 2.5 \cdot 10^{-29} \text{ e \cdot cm} \text{ for one year measurement} \]

Systematic error due to vertical electric fields and horizontal magnetic fields
### EDM Projects

#### Proton EDM
- **BNL**

#### Light-Ion EDM
- **Jülich**

<table>
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<tr>
<th>R&amp;D Activity</th>
<th>Goal</th>
<th>Test</th>
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<td>Internal Polarimeter</td>
<td>spin as a function of time</td>
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<td>&gt;$10^3$ s</td>
<td>EDM at COSY</td>
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<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>
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<td></td>
<td>$\rightarrow$ 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 coherence

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

At injection all spin vectors aligned (coherent)

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

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

Polarization not affected!

Longitudinal polarization vanishes!

In an EDM machine with frozen spin, observation time is limited.

Spin coherence time: $10^3$ s for measurement on $10^{-29}$ e·cm level
Spin Coherence EDM@COSY

RF Solenoid:
water-cooled copper coil in a ferrite box
• Length 0.6 m
• Frequency range 0.6 to 1.2 MHz
• Integrated field $\int B_{rms} \, dl \sim 1 \, \text{T} \cdot \text{mm}$

$$f_r = f_c (k \pm \gamma G)$$

SCT with sextupole correction > 100s

Spokesperson: E. Stephenson (IUCF)
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. $B^* = 0 \Rightarrow B_Y = \beta \times E_R$ ($\sim 70$ 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?
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
Computational Needs

- Particle revolutions: \( \gg 10^6 \) turns (1 seconds) → efficient simulation program
- Number of particle: \( 10^6 \) → 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 → roughly \( 10^{-18} \) radians per element
  → 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 of COSY- INFINITY on a Cray XE6 machine with 6384 nodes. Peak performance is 1.28 Petaflops/sec.

- 10^6 particles could be tracked in 10^6 turns.
- Each run generates 20 GByte output.

<table>
<thead>
<tr>
<th>#nodes (cores)</th>
<th>absolute timing (s)</th>
<th>speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>96 (2304)</td>
<td>5312</td>
<td>1.0</td>
</tr>
<tr>
<td>192 (4608)</td>
<td>2710</td>
<td>1.96</td>
</tr>
<tr>
<td>384 (9216)</td>
<td>1450</td>
<td>3.66</td>
</tr>
<tr>
<td>768 (18432)</td>
<td>740</td>
<td>7.18</td>
</tr>
</tbody>
</table>

Code Performance courtesy: Denis Zyuzin (FZJ)

Scaling behavior of COSY-INFINITY. This test was performed with 3rd order of nonlinearities, absolute timings per time step (s) and relative speedup normalized to 2304 cores are given.
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)

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<tr>
<th>#cores</th>
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<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>3076</td>
<td>7.95</td>
</tr>
</tbody>
</table>

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.

'28

Courtesy: Denis Zyuzin (FZJ)
Utilized Simulation Programs

Integrating program:

- differential equations of particle and spin motion in electric and magnetic fields are solved using Runge-Kutta integration
- accurate to sub-part per billion levels in describing the muon \((g-2)\) spin precession frequency
- integration step size is 0.5 ps, making it rather slow with a possible maximum tracking time of about 10 ms for a particle in the ring
- suitable to study effects that do not require a long numerical time
- for benchmarking the results of the much more efficient COSY Infinity

→ Talk by Y. Senichev tomorrow
Utilized Simulation Programs

For benchmarking

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
Conclusion / Outlook

EDM Measurement: Stepwise approach of the JEDI Project
- R&D work together with BNL
- First direct measurement at COSY
- Build a dedicated storage ring

Computational Needs
- Efficient simulation program on a super computer
- High precision spin simulation
- EDM spin kick and RF E/B spin flipper to be implemented
- Benchmarking with other simulation programs and COSY experiments
Brookhaven Proposal
A Magic Proton Ring for $10^{-29}$ e·cm

2 beams simultaneously rotating in a radial electric field

$E_R = 17$ MV/m

Beams are bunched with $h = 120$, $f = 90$ MHz

Clock-wise (CW) & Counter-clock-wise (CCW) storage

2012 proposal send to US-DoE

I.K.: Injection Kickers
P: Polarimeters
RF: RF-system
S: Sextupoles
Q: Quadrupoles
BPMs: ~70

Courtesy: Storage Ring EDM Collaboration
21 Institutions, 80 Collaborators
http://www.bnl.gov/edm
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 $\sim 10^{-27} \text{ e} \cdot \text{cm}$ 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 $\sim 10^{-29} \text{ e} \cdot \text{cm}$ for one year measurement

See http://www.bnl.gov/edm
## EDM Projects

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- **BNL**

### Light-Ion EDM
- **Jülich**

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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
\[ \rightarrow \text{achievable field of copper magnets of } \sim 0.15 \, \text{T.} \]
Simulation of Spin Rotations

<table>
<thead>
<tr>
<th>Parameters:</th>
<th>beam energy</th>
<th>$T_d=50$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>assumed EDM</td>
<td>$d_d=10^{-20}$ e·cm</td>
</tr>
<tr>
<td></td>
<td>E-field</td>
<td>10 kV/cm</td>
</tr>
</tbody>
</table>

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

Linear extrapolation of $P = \sqrt{P_x^2 + P_z^2}$ for a time period of $\tau_{sc}=1000$ s ($=3.7\cdot10^8$ turns)

EDM effect accumulates

Polarimeter determines $P_x$, $P_y$ and $P_z$

Number of turns

Polarimeter determines $P_x$, $P_y$ and $P_z$
## 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 <strong>at 10^{-24} e·cm</strong></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</td>
<td>Dedicated ring</td>
</tr>
<tr>
<td></td>
<td><strong>R&amp;D funded by ARD (Accelerator Research and Development) of HGF</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>EDM measurement for p, d, $^3$He <strong>at 10^{-29} e·cm</strong></td>
<td></td>
<td>Dedicated ring</td>
</tr>
</tbody>
</table>

**Time scale**

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