Accelerator related issues for storage ring EDM searches

July 12, 2012  |  Andreas Lehrach
on behalf of the JEDI collaboration
Outline

Introduction
Motivation and History of EDM Measurements

Spin Motion in Storage Rings
Thomas-BMT Equation
Invariant Spin Field
Frozen Spin Method

EDM Search in Storage Rings
Proton EDM Proposal (BNL)
All-In-One Ring Proposal (Jülich)
First Direct Measurement at COSY

Outlook
Electric Dipole Moments: What is it?

EDM: Permanent spatial separation of positive an negative charges

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

- 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
  \(d_n < 2.9 \times 10^{-26}\) e·cm
  PRL 97, 131801 (2006)

50 years of effort

Electro-weak standard model expectation: \(~10^{-32}\) 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>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>$&lt; 3 \times 10^{-26}$</td>
<td>$\sim 10^{-28}$</td>
</tr>
<tr>
<td>$^{199}\text{Hg}$</td>
<td>$&lt; 3.1 \times 10^{-29}$</td>
<td>$\sim 10^{-29}$</td>
</tr>
<tr>
<td>$^{129}\text{Xe}$</td>
<td>$&lt; 6 \times 10^{-27}$</td>
<td>$\sim 10^{-30} – 10^{-33}$</td>
</tr>
<tr>
<td>Proton</td>
<td>$&lt; 7.9 \times 10^{-25}$</td>
<td>$\sim 10^{-29}$</td>
</tr>
<tr>
<td>Deuteron</td>
<td>?</td>
<td>$\sim 10^{-29}$</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/](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 much 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:

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

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

\[
G = \frac{g - 2}{2},
\]

\[
d = \eta e \hbar / 4mc
\]

Magnetic Moment

EDM
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

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

\( \rightarrow G > 0 \) for \( \gamma > 1 \), if only electric fields are applied

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

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

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

\( \rightarrow \) 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)He</td>
<td>1.285</td>
<td>17.158</td>
<td>-0.051</td>
</tr>
</tbody>
</table>

“One machine with r ~ 30 m”
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

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

Polarization not affected!

Longitudinal polarization vanishes!

In an EDM machine with frozen spin, observation time is limited.
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 $\int B_{rms} \, dl \approx 1 \, \text{T} \cdot \text{mm}$

RF solenoid: on off on

SCT with sextupole correction >> 100s

Spokesperson: E. Stephenson (IUCF)
Statistical Sensitivity of an EDM Experiment

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

- \( P = 0.8 \) 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)

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

for one year measurement

Systematic error due to vertical electric fields and horizontal magnetic fields
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 $\sim 10^{-27}$ 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
## EDM Projects

### Proton EDM
- **BNL**

### Light-Ion EDM
- **Jülich**

<table>
<thead>
<tr>
<th>R&amp;D Activity</th>
<th>Goal</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal Polarimeter</strong></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></td>
</tr>
<tr>
<td></td>
<td>Full-scale polarimeter</td>
<td>EDM at COSY</td>
</tr>
<tr>
<td><strong>Spin Coherence Time</strong></td>
<td>&gt;10³ s</td>
<td>EDM at COSY</td>
</tr>
<tr>
<td><strong>Beam Position Monitor</strong></td>
<td>resolution 10 nm, 1 Hz BW</td>
<td>BNL RHIC IP</td>
</tr>
<tr>
<td></td>
<td>64 BPMs, 10⁷ s measurement time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>→ 1 pm (stat.) relative position (CW-CCW)</td>
<td></td>
</tr>
<tr>
<td><strong>E/B-field Deflector</strong></td>
<td>17 MV/m 2 cm plate separation, 0.15-0.5T</td>
<td>Jülich</td>
</tr>
</tbody>
</table>
Figure 1: “All-In-One” lattice for measuring EDM’s of protons, deuterons, and helions.
Iron-free, current-only, magnetic bending, eliminates hysteresis → achievable field of copper magnets of ~ 0.15 T.
Resonance Method with RF E/B Fields

First direct measurement in COSY developed by the Jülich study group

Radial RF-E and vertical RF-B field 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)

2. \( E^* = 0 \) \( \Rightarrow \) \( E_R = -\beta \times B_y \) „Magic RF Wienfilter“

„Direct“ EDM effect
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?
R&D Program JEDI
(Jülich Electric Dipole Moment Investigations)

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 of a precision simulation program for spin dynamics in a storage ring
   - COSY-Infinity, 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
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
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
## Summary / Outlook

### 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</td>
<td>Dedicated ring</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R&amp;D funded by ARD (Accelerator Research and Development) of HGF</td>
<td></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