Search for permanent electric dipole moments of protons and deuterons using storage rings

February 4, 2016

Frank Rathmann (on behalf of JEDI) Accelerator Seminar, Jefferson Lab
Preamble: The big challenges

This is the conventional HEP wisdom, but there is more than that ...
Search for permanent Electric Dipole Moments using storage rings
A most promising additional frontier: Precision
Outline

• Introduction
• Recent Achievements
  • Spin coherence time
  • Spin tune measurement
  • Study of magnetic machine imperfections
• Technical challenges
• Toward a first direct $p, d$ EDM measurement
• Conclusion
Introduction: Precision Frontier

Johann Jakob Balmer (1885)

Striving for the ultimate precision/sensitivity: example hydrogen
Introduction: Precision Frontier

Johann Jakob Balmer (1885)

Willis E. Lamb (1947)

Balmer Series → H-atom

Lamb-shift (NP 1955) → QED

g/2 = 1 + α/2π

≈ 1.00116

Striving for the ultimate precision/sensitivity

f.rathmann@fz-juelich.de

Search for permanent Electric Dipole Moments using storage rings
**Introduction: Precision Frontier**

G. Gabrielse et al. (2008)

Johann Jakob Balmer (1885)

V. Weisskopf: “To understand hydrogen is to understand all of physics”

\[ g/2 = 1.001\,159\,652\,180\,73(28) \times 10^{-12} \]

(...)

Electron MDM \( \rightarrow \) SM test

Balmer Series \( \rightarrow \) H-atom

f.rathmann@fz-juelich.de
Five questions:

1. Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?
2. What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?
3. Why can't the Standard Model predict a particle's mass?
4. Are quarks and leptons actually fundamental, or made up of even more fundamental particles?
5. Why are there exactly three generations of quarks and leptons? How does gravity fit into all of this?

From http://particleadventure.org/beyond_start.html
Assertion: Universe „started“ with **equal amounts** of matter and antimatter!
Physics: **Baryogenesis**

Very soon, a slight **asymmetry developed** (CP / T violation)

Matter | Anti-matter

10,000,000,000 | 10,000,000,01

Search for permanent Electric Dipole Moments using storage rings
Physics: Baryogenesis

Big Bang

Early Universe

Matter anti-matter annihilation → photons

All the anti-matter annihilated with matter
Physics: Baryogenesis

Big Bang → Early Universe → Today

Matter + Anti-matter → Annihilation → Photons

Now, only matter is left over!
Physics: Baryogenesis

Ingredients for baryogenesis: 3 Sakharov conditions

(1) Baryon number $B$ violation
via:
- Grand unification
- Axial anomaly in SM
- Majorana mass

MODEL?

(2) $C, CP$ violation
via:
- Strong $CP$ violation in SM
- Electroweak $CP$ violation
- Majorana mass
- Beyond the SM
- Spontaneous $CP$ violation

(3) Non equilibrium
via:
- Expansion of the universe and out of equilibrium decay
- (First order) phase transition

(1967)
Physics: Observed Baryon Asymmetry

<table>
<thead>
<tr>
<th></th>
<th>((n_B - n_{\bar{B}})/n_\gamma)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observed</strong></td>
<td>((6.11 \pm 0.19) \times 10^{-10})</td>
<td>WMAP+COBE (2003)</td>
</tr>
<tr>
<td><strong>SM exp.</strong></td>
<td>(~10^{-18})</td>
<td></td>
</tr>
</tbody>
</table>

Carina Nebula: Largest-seen star-birth regions in the galaxy

Why this strange number? Why not zero?

- Search for new physics beyond the standard model
- Mystery of **missing antimatter** addresses the puzzle of our existence
Charge symmetric
→ No EDM ($d = 0$)

Do particles (e.g., electron, nucleon) have an EDM?

$\vec{\mu}$: MDM
$\vec{d}$: EDM
EDMs: Discrete Symmetries

Permanent EDMs violate both $P$ and $T$ symmetry. Assuming $CPT$ to hold, $CP$ violated also.

Not Charge symmetric

(aligned with spin)
Introduction: Precision Frontier

Example: Neutron (nEDM)

Search for Electric Dipole Moments (EDM) of fundamental particles

Introduction: Precision Frontier

Nucleon → Earth

Current upper limit → separation ≈ size of a hair

An EDM is VERY small!!

Search for permanent Electric Dipole Moments using storage rings
Measurement principle: Neutral particle EDM

Particle in ground state: \( s = \frac{1}{2} \)

1. Reverse \( \vec{E} \)
2. Keep \( \vec{B} \) the same

\[
\omega_1 = \frac{2\mu B + 2dE}{h} \\
\Rightarrow \omega_1 - \omega_2 = \frac{4dE}{h}
\]

\[
\omega_2 = \frac{2\mu B - 2dE}{h}
\]

One challenge: Shield external sources of \( B \) to levels \( |B_{ext}| < 1 \text{ nT.} \)
Search for permanent Electric Dipole Moments using storage rings

J.M. Pendlebury: „nEDM has killed more theories than any other single exp‘t“

Physics Potential of EDMs

The Measurement of EDMs: History of the experimental progress

\[ d(\text{proton}) < 8 \cdot 10^{-25} \]

\[ d(\text{neutron}) < 3 \cdot 10^{-26} \]

\[ d(\text{electron}) < 8 \cdot 10^{-29} \]
Introduction: Why charged particle EDMs?

- No direct measurements of charged hadron EDMs
- Potentially higher sensitivity than neutrons
  - longer life time
  - more stored polarized protons/deuterons
  - larger electric fields
- Approach complimentary to neutron EDM
- $d_d = d_p + d_n \Rightarrow$ access to $\theta_{QCD}$
- EDM of a single particle not sufficient to identify CP-violating source

Charged particle EDM experiments can potentially provide a higher sensitivity than nEDM
EDMs: Naive estimate of the nucleon EDM scale

Khriplovich & Lamoreux (1997); Nikolaev (2012)

- \( CP \) \& \( P \) conserving magnetic moment \( \approx \) nuclear magneton \( \mu_N \)
  \[
  \mu_N = \frac{e}{2m_p} \sim 10^{-14} \text{ e cm}
  \]

- A non-zero EDM requires
  - \( P \) violation: the price to pay is \( \approx 10^{-7} \), and
  - \( CP \) violation (from K-decays): the price to pay is \( \approx 10^{-3} \)

- In summary:
  \[
  |d_N| \approx 10^{-7} \times 10^{-3} \times \mu_N \approx 10^{-24} \text{ e cm}
  \]

- In SM (without \( \theta \) term):
  \[
  |d_N^{SM}| \approx 10^{-7} \times 10^{-24} \approx 10^{-31} \text{ e cm}
  \]

⇒ Region to search for BSM physics \( (\theta_{QCD} = 0) \) using nucleon EDMs:

\( 10^{-24} \text{ e cm} > |d_N| > 10^{-31} \text{ e cm} \)
**Physics: Present limits of EDMs**

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

<table>
<thead>
<tr>
<th>Particle/Atom</th>
<th>Current EDM Limit</th>
<th>Future Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>&lt; $8.7 \times 10^{-29}$</td>
<td></td>
</tr>
<tr>
<td>Muon</td>
<td>&lt; $1.8 \times 10^{-19}$</td>
<td></td>
</tr>
<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>

- No direct measurements of electron (ThO molecule) or proton ($^{199}$Hg) EDMs
- No measurement at all of deuteron EDM

Large effort on worldwide scale to improve limits and to find EDMs
Physics: 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
  - @FNL
  - @JPARC

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

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

P. Harris, K. Kirch … A large worldwide effort

Search for permanent Electric Dipole Moments using storage rings
Goal: provide $\sigma_{\text{syst}}$ to the same level

![Image](image.png)

Concept: Experimental requirements

- High precision, primarily electric storage ring
  - alignment, stability, field homogeneity, and shielding from perturbing magnetic fields
- High beam intensity ($N = 4 \cdot 10^{10}$ per fill)
- Stored polarized hadrons ($P = 0.8$)
- Large electric fields ($E = 10$ MV/m)
- Long spin coherence time ($\tau_{\text{SCT}} = 1000$ s)
- Efficient polarimetry (analyzing power $A_y \approx 0.6, f = 0.005$)

$$\sigma_{\text{stat}} \approx \frac{1}{\sqrt{N \cdot f \cdot \tau \cdot P \cdot A_y \cdot E}} \Rightarrow \sigma_{\text{stat}}(1\ \text{year}) = 10^{-29}\ \text{e} \cdot \text{cm}$$

**Goal:** provide $\sigma_{\text{syst}}$ to the same level
Concept: Frozen spin Method

For transverse electric and magnetic fields in a ring, the anomalous spin precession is described by the Thomas-BMT equation:

\[
\vec{\Omega}_{MDM} = \frac{q}{m} \left\{ \vec{B} - \frac{\gamma G}{\gamma + 1} \vec{\beta} (\vec{\beta} \cdot \vec{E}) - \left[ G - \frac{1}{\gamma^2 - 1} \right] \frac{\vec{\beta} \times \vec{E}}{c} \right\} \quad \left( G = \frac{g - 2}{2} \right)
\]

Magic condition: Spin along momentum vector

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

\[
E = \frac{GBc\beta\gamma^2}{1 - G\beta^2\gamma^2} \approx GBc\beta\gamma^2, \text{ where } E = E_{\text{radial}} \text{ and } B = B_{\text{vertical}}
\]

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

\[
G - \left( \frac{m}{p} \right)^2 = 0 \Rightarrow p = \frac{m}{\sqrt{G}} = 700.74 \text{ MeV/c} \quad (\text{magic})
\]

→ Magic rings to measure EDMs of free charge particles
Concept: **Rings for EDM searches**

- Place particles in a storage ring
- **Align spin along** momentum ("freeze" horizontal spin precession)
- Search for time development of vertical polarization

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

**New Method to measure EDMs of charged particles:**
- Magic rings with spin frozen along momentum
- Polarization buildup \( P_y (t) \sim d \)
Concepts: *Magic Storage ring*

A *magic* storage ring for protons (electrostatic), deuterons, …

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

<table>
<thead>
<tr>
<th>particle</th>
<th>( p ) (MeV/c)</th>
<th>( T ) (MeV)</th>
<th>( E ) (MV/m)</th>
<th>( B ) (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>701</td>
<td>232.8</td>
<td>16.789</td>
<td>0.000</td>
</tr>
<tr>
<td>deuteron</td>
<td>1000</td>
<td>249.9</td>
<td>−3.983</td>
<td>0.160</td>
</tr>
<tr>
<td>(^3\text{He})</td>
<td>1285</td>
<td>280.0</td>
<td>17.158</td>
<td>−0.051</td>
</tr>
</tbody>
</table>

Possible to measure \( p, d, \(^3\text{He}\)\) using **one** machine with \( r \sim 25 \text{ m} \)
**Magnetic fields:**

- Radial field $B_r$ mimics EDM effect when $\mu \times B_r \approx d \times E_r$
- With $d = 10^{-29}$ e·cm in a field of $E = 10$ MV/m,

$$B_r = \frac{dE_r}{\mu_n} = \frac{10^{-31} \cdot 10^7 \text{eV}}{3.152 \cdot 10^{-8} \text{eV/T}} = 3.1 \cdot 10^{-17} \text{T}$$

- **Solution:** Use two beams *simultaneously*, clockwise (CW) and counter-clockwise (CCW), the vertical separation of the beam orbits is sensitive to $B_r$.

---

Use CW and CCW beams to tackle systematics
Recent Progress: Magnetic shielding

Next generation nEDM experiment under development at TUM (FRM II):

- **Goal:** Improve present nEDM limit by factor 100.
- Experiment shall use multi-layer shield.
- Applied magnetic field: $B \approx 1 - 2.5 \mu T$.

At mHz frequencies, damping of $|B_{\text{ext}}| \approx 1 \cdot 10^6$ achieved
Concept: Systematics, Orbit splitting (Dave Kawall)

- Splitting of beam orbits: \( \delta y = \pm \frac{\beta c R_0 B_r}{E_r Q_y^2} = \pm 1 \cdot 10^{-12} \) m
- \( Q_y \approx 0.1 \) denotes the vertical betatron tune
- Modulate \( Q_y = Q_y^0[1 - m \cos(\omega_m t)] \), with \( m \approx 0.1 \)
- Splitting corresponds to \( B \approx 0.4 \cdot 10^{-3} \) fT
- In one year of measurement: \( 10^4 \) fills of 1000 s each
  \( \Rightarrow \sigma_B = 0.4 \cdot 10^{-1} \) fT per fill

Required sensitivity \( \approx 1.25 \) fT/\( \sqrt{\text{Hz}} \), achievable with state-of-the-art SQUID magnetometers.
Outline

- Introduction
- **Recent Achievements**
  - Spin coherence time
  - Spin tune measurement
  - Study of magnetic machine imperfections
- Technical challenges
- Toward a first direct $p, d$ EDM measurement
- Conclusion
Spin closed orbit

one particle with magnetic moment makes one turn

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

“spin closed orbit vector”

\[ 2\pi \nu_s = 2\pi \gamma G \]

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

The number of spin precessions per turn is called spin tune \( \nu_s \)
Challenge: Spin coherence time (SCT)

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 along $\hat{n}_{co}$ not affected!

Situation very different, when you deal with $\vec{S} \perp \hat{n}_{co}$ machines with frozen spin.

Longitudinal polarization vanishes!

At injection all spin vectors aligned
Later, spin vectors are out of phase in the horizontal plane

In a machine with frozen spins the buildup time to observe a polarization $P_y(t)$ is limited by $\tau_{SCT}$. 
EDM at COSY: COoler SYnchrotron

Cooler and storage ring for (polarized) protons and deuterons

\[ p = 0.3 - 3.7 \text{ GeV/c} \]

Phase space cooled internal & extracted beams

… an ideal starting point for EDM search

f.rathmann@fz-juelich.de

Search for permanent Electric Dipole Moments using storage rings
Outline

- Introduction
- Recent Achievements
  - Spin coherence time
  - Spin tune measurement
  - Study of magnetic machine imperfections
- Technical challenges
- Toward a first direct $p, d$ EDM measurement
- Conclusion
Spin coherence time: Experimental investigation

1. Vertically polarized deuterons stored in COSY at $p \approx 1 \frac{\text{GeV}}{c}$.

2. The polarization is flipped into horizontal plane with RF solenoid (takes $\approx 200 \text{ ms}$).

3. Beam slowly extracted on Carbon target with ramped bump or by heating the beam.

4. Horizontal (in-plane) polarization determined from Up-Do asymmetry in the detector.

Experimental investigations of SCT in storage ring: Keep track of the event time and revolution time in each turn during a cycle of a few hundred seconds.
Spin coherence time: Beam setups

Two different beam setups were used:

1. Large $\frac{\Delta p}{p}$, and
2. large horizontal beam emittance.

![Graph showing beam setups with storage time and processes like eCooling, Bunching, Extraction, and Polarization rotation.](graph.png)
Polarimeter: Experimental investigation of SCT

Deuterons at $p \approx 1 \text{ GeV/c}$, $\gamma = 1.13$ and $\nu_s = \gamma \cdot G = -0.161$

$$N_{U,D} \propto 1 \pm \frac{3}{2} p \cdot A_y \cdot \sin(\nu_s f_{\text{rev}} t), \text{ where } f_{\text{rev}} \approx 781 \text{ kHz}$$
Polarimeter: Determination of SCT

Observed experimental decay of the asymmetry $\varepsilon_{UD} = \frac{N_D - N_U}{N_D + N_U}$ as function of time, $\varepsilon_{UD}(t) \approx P(t)$.

Horizontal Asymmetry Run: 2042

$\tau_{SCT} \approx 20\ s$
Polarimeter: Optimization of SCT

Using sextupole magnets in the machine, higher order effects can be corrected, and the SCT is substantially increased.

\[
\tau_{\text{SCT}} \approx 400 \text{ s}
\]
**SCT: Chromaticity studies**

Chromaticity $\xi$ defines the betatron tune change with respect to the momentum deviation

$$\frac{\Delta Q_{x,y}}{Q_{x,y}} = \xi_{x,y} \cdot \frac{\Delta p}{p}$$

- Strong connection between $\xi_{x,y}$ and $\tau_{SC}$ observed.
- COSY Infinity based model predicts negative natural chromaticities $\xi_x$ and $\xi_y$.
- Measured natural chromaticity: $\xi_y > 0$ and $\xi_x < 0$.

Maximal horizontal polarization lifetimes from scans with a horizontally wide or a long beam agree well with the lines of $\xi_{x,y} \approx 0$.

**Crucial for achieving a large $\tau_{SC}$ is careful adjustment of $\xi_{x,y}$**.
More progress on $\tau_{\text{SCT}}$: Spring 2015

Way beyond anybody’s expectations $\rightarrow \sigma_{\text{stat}} \approx \tau_{\text{SCT}}^{-1}$
Outline

• Introduction
• Recent Achievements
  • Spin coherence time
  • **Spin tune measurement**
    • Study of magnetic machine imperfections
• Technical challenges
• Toward a first direct $p, d$ EDM measurement
• Conclusion
Spin tune $\nu_s$: How to measure it?

$\nu_s \equiv$ Number of spin precessions revolution, a priori not known ($\approx \gamma G$)
- Detector rate is $\approx 5$ kHz, $f_{\text{rev}} = 781$ kHz $\rightarrow$ one hit in detector per 25 beam revolutions

Scan $\nu_s$ in an interval around $\gamma G$ and find maximum of asymmetry $\varepsilon_{UD}$

Solution: Map all events into one spin oscillation period
Spin tune: Determination of $\nu_s$

Monitor phase of asymmetry with fixed $\nu_s$ in a 100 s cycle.

$$\nu_s(n) = \nu_s^\text{fix} + \frac{1}{2\pi} \frac{d\phi(n)}{dn} = \nu_s^\text{fix} + \Delta \nu_s(n)$$

Spin tune $\nu_s$ determined to $\approx 10^{-8}$ in 2 s time interval, and in a 100 s cycle at $t \approx 40$ s to $\approx 10^{-10}$ (PRL 115, 094801 (2015))
New precision tool: Spin tune determination

Observed behavior of subsequent cycles

- Study long term stability of an accelerator
- Develop feedback systems to minimize variations
- Phase-locking the spin precession to RF devices possible
Outline

- Introduction
- Recent Achievements
  - Spin coherence time
  - Spin tune measurement
  - Study of magnetic machine imperfections
- Technical challenges
- Toward a first direct $p, d$ EDM measurement
- Conclusion
Systematic study: Machine imperfections using two straight section solenoids

Systematic effects from machine imperfections limit the achievable precision in an EDM experiment using an RF $E \times B$ Wien filter.

**Idea:** The precise determination of the spin tune $\left( \frac{\Delta \nu_s}{\nu_s} \approx 10^{-10} \text{ in one cycle} \right)$ can be exploited to map out the magnetic imperfections of COSY.

COSY provides two solenoids in opposite straight sections:

1. one of the compensation solenoids of the 70 kV cooler: $\int B_z dz \approx 0.15 \text{ Tm}$,
2. The main solenoid of the 2 MV cooler: $\int B_z dz \approx 0.54 \text{ Tm}$.

Both are available dynamically in the cycle, *i.e.*, their strength can be adjusted on flat top.
Systematic study: Simulation of one imperfection spin kick for deuterons at 970 MeV/c

**Ideal machine** with vanishing static imperfections: *Saddle point at the origin*

- Sea level at $G\gamma (= 0.16) - 5 \cdot 10^{-7}$

**Intrinsic imperfection** kick $\alpha_x = 0.001$ shifts saddle point away from origin

- Location of imperfection: $\Theta^* = \pi/3$
Systematic study: **Thomas-BMT eq. \((d \neq 0)\) in magnetic machine**

**Goal:** explore dynamics and systematic limitations of EDM searches in magnetic ring

\[
\frac{d\mathbf{s}}{dt} = \mathbf{s} \times \left( \Omega_{\text{MDM}} + \Omega_{\text{EDM}} \right)
\]

\[
\mathbf{\mu} = g \frac{q \hbar}{2m} \mathbf{s} = (G + 1) \frac{q \hbar}{m} \mathbf{s}, \quad \text{and} \quad \mathbf{d} = \frac{\eta q \hbar}{2m} \mathbf{s}
\]

\[
\Omega_{\text{MDM}} = \frac{q}{m} \left\{ G \cdot \vec{B} - \frac{\gamma G}{\gamma + 1} \hat{\beta} \cdot \vec{E} - \left[ G - \frac{1}{\gamma^2 - 1} \right] \hat{\beta} \times \vec{E} \right\}
\]

\[
\Omega_{\text{EDM}} = \frac{\eta q}{2mc} \left\{ \vec{E} - \frac{\gamma}{\gamma + 1} \hat{\beta} (\hat{\beta} \cdot \vec{E}) + c \hat{\beta} \times \vec{B} \right\}
\]

BMT for magnetic machine with \(d \neq 0\):

\[
\frac{d\mathbf{s}}{dt} = \frac{q}{m} \left\{ G \cdot \vec{B} + \frac{\eta}{2} \left( \hat{\beta} \times \vec{B} \right) \right\}
\]

Interaction of EDM with motional E-field \((\hat{\beta} \times \vec{B})\) tilts stable spin axis:

\[
\vec{n}_{co} = \hat{e}_x \sin \xi + \hat{e}_y \cos \xi \quad \tan \xi = \frac{\eta}{2G} \beta \quad \eta = 2d \frac{m}{q}
\]

Misalignment of magnetic elements produces in-plane imperfection magnetic fields:

\[
\vec{n}_{co} = \hat{e}_x c_1 + \hat{e}_y c_2 + \hat{e}_z c_3
\]

Non-vanishing \(c_1\) and \(c_3\) generate background to the EDM-signal of an ideal imperfection-free machine \((c_1 = \sin \xi, c_2 = \cos \xi\) and \(c_3 = 0\)).

The challenge is to control this background:  
An accuracy \(\Delta c_{1,3} \approx 10^{-6}\) rad amounts to a sensitivity \(d = 10^{-20}\) e \(\cdot\) cm.
Systematic study: Imperfection measurement

Probing the in-plane imperfection fields by introducing artificial imperfections and looking for the spin tune response

Use the compensation and e-cooler solenoids in straight sections (points 1 and 2): spin kicks $\chi_1$ and $\chi_2$.

The values of $(c_1, c_2)$, and $(c_3, c_3^*)$ depend on spin kicks in non-vertical imperfection fields in the arcs $\rightarrow$ spin tune perturbed:

$$\nu_s = G\gamma + O(c_1^2, c_3^2, c_1^*^2, c_3^*^2)$$

Probe the in-plane imperfection fields by introducing well-known artificial imperfections $\chi_1$ and $\chi_2$. 
Systematic study: **Measurement of spin tune shift**

Take multiple measurements with different $\chi_1, \chi_2$, build a spin tune map $\Delta \nu_s(\chi_1, \chi_2)$.
Systematic study: Mapping machine imperfections

Map translated to

\[ y_+ = \frac{\chi_1 + \chi_2}{2} \]

\[ y_- = \frac{\chi_1 - \chi_2}{2} \]

\[ \Rightarrow \quad \Delta v_s \approx y_+^2, y_-^2 \]

From the map taken on 18+19.09.2014, with the baseline spin tune at \( v_s = -0.160971917 \), one finds:

\[ c_3 = -0.0034 \pm 2 \cdot 10^{-7} \]

\[ c_3^* = -0.0021 \pm 6 \cdot 10^{-8} \]
Systematic study: Mapping imperfections

- Extremum of spin tune map is saddle point at $y_+, y_- = O(c_3, c_3^*)$.
- Once baseline spin tune $\nu_s$ determined, $(c_3, c_3^*)$ are only fit parameters.
- Solenoids only are not sensitive to $c_1$, $c_1^* y \rightarrow$ static WF with $B_x$ and $E_y$.

New technique allows one to experimentally reconstruct the components of the spin closed orbit $\vec{n}_{co}$ in a storage ring with unprecedented precision (not achievable from polarization measurements alone).
Outline

• Introduction
• Recent Achievements
  • Spin coherence time
  • Spin tune measurement
  • Study of magnetic machine imperfections
• Technical challenges
  • Beam position monitors
  • Electrostatic deflectors
• Toward a first direct $p, d$ EDM measurement
• Conclusion
Technical challenges: Overview

Charged particle EDM searches require the development of a new class of high-precision machines with mainly electric fields for bending and focussing.

Issues are:

- Electric field gradients (~17 MV/m) at ~2 cm plate distance
- Spin coherence time (≥ 1000 s)
- Continuous polarimetry (< 1 ppm)
- Beam position monitoring (10 nm)
- Spin tracking

These issues must be addressed experimentally at existing facilities
Challenge BPMs: Rogowski coil

- Integral signal measures beam current
- Quadrant signals sensitive to position

Installed in ANKE target chamber

For bunched beams, sum signal of Rogowski coil can be used as a beam current monitor.
Challenge BPMs: Rogowski coil

- Integral signal measures beam current
- Quadrant signals sensitive to position

EDM experiments use bunched beams:
- Rogowski coil system well-suited.
- Small size allows for flexible installation (→ Stripline RF Wien filter)

Tests at COSY can be carried out parasitically.

Quadrant signals of Rogowski coil sensitive to beam position.

\[
\begin{align*}
x &= \frac{\text{left} - \text{right}}{\text{left} + \text{right}} \\
y &= \frac{\text{up} - \text{down}}{\text{up} + \text{down}}
\end{align*}
\]

Dynamic range:
- \(10^8 - 10^{11}\) particles
- Maximum deviation from axis \(\approx 40\) mm
- Resolution: 10 nm
Challenge: Niobium electrodes

Evaluation of niobium as candidate electrode material for dc high voltage photoelectron guns

DPP stainless steel

fine-grain Nb

large-grain Nb

single-crystal Nb

Large-grain Nb at plate separation of a few cm yields ~20 MV/m
Challenge: Electric deflectors for magic rings

Electrostatic separators at Tevatron were used to avoid unwanted $\bar{p}p$ interactions - electrodes made from stainless steel

Routine operation at 1 spark/year at 6 MV/m

May 2014: Transfer of separator unit plus equipment from FNAL to Jülich

Need to develop new electrode materials and surface treatments
Challenge: Electric deflectors for magic rings

1. Deflector development will use scaled models ~ 1: 10
   • Electric fields are the same, but voltages < 20 kV
   • Avoids shielding of x-rays
   • Allows tests to be done in usual lab environment

2. Development of real size combined elements (E & B)
   • Begin EDM search with deuterons
   • Use existing dipole magnet of internal ANKE spectrometer
   • Allows for tests with beam

Development of new deflector materials, treatment methods towards high fields $E \sim 20$ MV/m, and combined E-B deflectors
Electrostatic deflectors: Clean room at RWTH

Prof. Marquardt chairman of FZJ directors board and Prof. Schmachtenberg Rektor of RWTH Aachen

Test bench at RWTH Aachen

Development of mall scale deflector elements in cooperation with RWTH (Kirill Grigoriev).

But: Result need to be verified using 1:1 deflector models (Jülich)

f.rathmann@fz-juelich.de

Search for permanent Electric Dipole Moments using storage rings
Electrostatic deflectors: Some results

Different shape of the electrodes

Material: Stainless steel, Aluminum
Mechanical polished and cleaned

**Stainless steel**
Two small half-spheres (R = 10mm)
17kV at 1mm distance → **17 MV/m**

Half-sphere vs. flat surface
12kV at 0.05 mm distance → **240 MV/m**

**Aluminum**
Two small half-spheres (R = 10mm)
3kV at 0.1mm distance → **30 MV/m**
Large scale elements: **ANKE chicane at COSY**

**Idea** (Jürgen Böker): Produce E-B deflector by insertion of deflector element into D2 magnet chamber.
Large-scale E-B deflector development

D2 magnet:

\[ B_{\text{max}} = 1.6 \text{ T}, m = 64 \text{ t} \]

**Deflector:** Length: 1020 mm, Height: 90 mm, Gap: 40 – 80 mm

Begin development with straight elements
Outline

• Introduction
• Recent Achievements
  • Spin coherence time
  • Spin tune measurement
  • Study of magnetic machine imperfections
• Technical challenges
• Toward a first direct $p, d$ EDM measurement
• Conclusion
Idea for proof-of-principle srEDM experiment

Use an RF technique:

• RF device operates on some harmonic of the spin precession frequency
• accumulate EDM signal with time

Use COSY for a first direct $p$ and $d$ EDM measurement
Direct EDM measurement: Resonance Method with „magic“ RF Wien filter

Avoids coherent betatron oscillations of beam. Radial RF-E and vertical RF-B fields to observe spin rotation due to EDM. Approach pursued for a first direct measurement at COSY.

\[ E^* = 0 \Rightarrow E_R = -\beta \times B_y \]

„Magic RF Wien Filter“
no Lorentz force
\[ \rightarrow \text{Indirect EDM effect} \]

In-plane polarization
Observable:
Accumulation of vertical polarization during spin coherence time

Statistical sensitivity for \(d_d\) in the range \(10^{-23}\) to \(10^{-24}\) e·cm range possible.
- Alignment and field stability of ring magnets
- Imperfection of RF-E(B) flipper
First direct EDM measurement: Resonance Method for deuterons

Parameters:  
beam energy \( T_d = 50 \text{ MeV} \)
assumed EDM \( d_d = 10^{-24} \text{ e}\cdot\text{cm} \)
E-field \( 30 \text{ kV/cm} \)

\[ L_{RF} = 1 \text{ m} \]

EDM effect accumulates in \( P_y \) (see Phys. Rev. ST AB 16, 114001 (2013))
First direct Edm measurement: Resonance Method for deuterons

Parameters:
- beam energy: \( T_d = 50 \text{ MeV} \)
- assumed EDM: \( d_d = 10^{-24} \text{ e} \cdot \text{cm} \)
- E-field: 30 kV/cm
- \( L_{RF} = 1 \text{ m} \)

Linear extrapolation of \( P_y \) for a time period of \( \tau_{sc} = 1000 \text{ s} \) (= 3.7 \cdot 10^8 turns) yields a sizeable \( P_y \sim 10^{-3} \).
RF $E \times B$ Wien Filter: Resonance condition

Deuterons at 970 MeV/c: $\beta = 0.459; \gamma = 1.126; G = -0.142\,987$

$$f_{RF} = f_{\text{rev}}(\gamma G \pm K), \quad K \in \mathbb{Z}$$

$$f_{\text{rev}} \approx 750 \, \text{kHz}$$

$$\nu_s = \gamma G = -0.16098$$

<table>
<thead>
<tr>
<th>$K$</th>
<th>0</th>
<th>1</th>
<th>−1</th>
<th>2</th>
<th>−2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{RF}/\text{kHz}$</td>
<td>120</td>
<td>629</td>
<td>871</td>
<td>1380</td>
<td>1621</td>
</tr>
</tbody>
</table>

Frequency range RF Wien filter prototype
RF $\mathbf{E} \times \mathbf{B}$ Wien Filter: Prototype commissioning

EDM measurement concept: RF Wien filter to accumulate EDM signal

- RF-B-Dipole
  - ferrite blocks
  - coil: 8 windings, length 560 mm

- RF-E-Dipole
  - two electrodes in vacuum camber, 50 $\mu$m stainless steel
  - distance 52 mm, length 580 mm
  - ceramic beam chamber
  - two separate resonance circuits

Shielding Box

f.rathmann@fz-juelich.de
RF E × B Wien Filter: Field calculations

Main field component
\[ \hat{B}_x = 0.058 \text{ mT at } y = 0, \quad I = 1 \text{ A}, \]
\[ \int \hat{B}_x dz = 0.035 \text{ Tmm} \]

Main field component
\[ \hat{E}_y = 7594 \text{ V/m at } y = 0, \]
\[ U = 395 \text{ V}, \quad \int \hat{E}_y dz = 4818 \text{ V} \]

Integral compensation of Lorentz force
\[ \int F_y dz = 0 \text{ at } y = 0 \]
RF Wien Filter: Measurement of Resonance Strengths

- **Continuous polarimetry**: Fixed frequency scans for resonance determination
- Damping due to decoherence
- Cross-ratio of UD-asymmetries used.
- Minimum vertical polarization oscillation frequency gives resonance strength:
  \[ \epsilon = \frac{f_{P_y,\text{min}}}{f_{\text{rev}}} \]
RF $\mathbf{E} \times \mathbf{B}$ Wien Filter: Preliminary Results

RF solenoid:

$$f_{P_y} \approx \frac{1 + G}{4\pi} \int \frac{\hat{B}_\parallel dl}{B \rho}$$

RF Wien filter:

$$f_{P_y} \approx \frac{1 + G}{4\pi\gamma} \int \frac{\hat{B}_\perp dl}{B \rho}$$

RF dipole:

$$f_{P_y} \approx \frac{1 + \gamma G}{4\pi} \int \frac{\hat{B}_\perp dl}{B \rho}$$

From driven vertical oscillation at fixed frequency

$$\left(2 - Q_y\right)f_{RF}$$ (kHz)

From froissart-Stora scans

$\xi_{FS}$ / $\xi_{BF}$

RF $\mathbf{E} \times \mathbf{B}$ Wien filter prototype performs like an RF solenoid

f.rathmann@fz-juelich.de

Search for permanent Electric Dipole Moments using storage rings
Development of waveguide RF Wien Filter

Device developed at IKP in cooperation with:

- **RWTH Aachen, Institute of High Frequency Technology:**
  - Dirk Heberling, Dominik Hölscher, and PhD Student Jamal Slim
- **ZEA-1 of Jülich:**
  - Helmut Soltner, Lars Reifferscheidt, Heidi Straatmann

Device will be installed in PAX low-β section
Some features of the new RF Wien filter

Waveguide provides $\vec{E} \times \vec{B}$ by design.

Aim is to build the best possible device with respect to electromagnetic performance, mechanical tolerances, etc.
Internal structure of the device

Ceramic insulators

Copper electrodes with the trapezium shaping at the edges

Sliding connector to RF

Mechanical support for electrodes

Clamps supporting the Ferrit cage

Inner support tube

Design completed, production started, device available in fall 2016.
Electromagnetic field simulations

- Full-wave simulation with CST Microwave Studio
- Each simulation required ~12 hours of computer time

Excellent cooperation with RWTH and ZEA
Lorentz force compensation

Providing minimal integral Lorentz force requires careful shaping of electrodes and all other components

\[ \vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) \]

Lorentz force integral with \( \vec{v} \) along Wien filter axis

\[
\frac{q}{\ell} \int_{-\ell/2}^{\ell/2} \begin{pmatrix}
E_x - c\beta B_y \\
E_y + c\beta B_x \\
E_z
\end{pmatrix} \, dz = \begin{pmatrix}
5.97 \times 10^{-3} \\
7.97 \times 10^{-3} \\
1.27 \times 10^{-21}
\end{pmatrix} \text{ eV/m}
\]

\[
\int_{-\ell/2}^{\ell/2} \vec{B} \, dz = \begin{pmatrix}
2.73 \times 10^{-9} \\
0.047 \\
6.96 \times 10^{-7}
\end{pmatrix} \text{ T mm}
\]

Mechanical design completed. Continued work on RF driving circuit. Goal is to reach \( \int Bdl \sim 0.5 \text{ Tmm possible.} \)
RF E × B Wien Filter: Resonance conditions

\[ f_{RF} = f_{rev}(\gamma G \pm K), \; K \in \mathbb{Z} \]

<table>
<thead>
<tr>
<th></th>
<th>( p )</th>
<th>( f_{rev}/kHz )</th>
<th>( G )</th>
<th>( \beta )</th>
<th>( \gamma )</th>
<th>( \gamma G )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d )</td>
<td>970.0</td>
<td>750.2</td>
<td>−0.143</td>
<td>0.459</td>
<td>1.126</td>
<td>−0.161</td>
</tr>
<tr>
<td>( p )</td>
<td>521.1</td>
<td>752.6</td>
<td>1.793</td>
<td>0.486</td>
<td>1.144</td>
<td>2.051</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( K )</th>
<th>−4</th>
<th>−3</th>
<th>−2</th>
<th>−1</th>
<th>0</th>
<th>+1</th>
<th>+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>f_{RF}</td>
<td>/kHz )</td>
<td>( d )</td>
<td>1621.2</td>
<td>871.0</td>
<td>120.8</td>
<td>629.4</td>
</tr>
<tr>
<td>( p )</td>
<td>1545.6</td>
<td>752.6</td>
<td>40.3</td>
<td>833.2</td>
<td>1626.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Frequency range RF Wien filter prototype (Gebel/Mey)

New waveguide RF Wien filter will provide resonance conditions for deuterons and protons for a number harmonics \( K \).
Concept for first measurements

Simulations with COSY-INF. and RF Wien filter \((E_x, B_y)\) in EDM buildup mode.

\[
\hat{d} = \frac{\eta q \hbar}{2mc} \hat{S}
\]

\[
d = 5 \cdot 10^{-20} \text{ e cm}
\]

EDM hidden underneath imperfections from magnet misalignments.
Concept for first measurements

- With an RF Wien filter of $\int Bdl = 0.05$ Tmm, $\sigma_{\text{stat}} \sim 2 \cdot 10^{-22}$ e cm can be reached in 1000 s.

Randomized error standard deviation of 0.1 mm $\rightarrow$ RMS displacements $\sim$1mm. Contribution to buildup from misalignments similar to EDM for $\eta = 10^{-4}$, $d = 5 \cdot 10^{-19}$ e cm.

M Rosenthal et al, IBIC 2015
Results from the December 2015 run at COSY

1. Rotate deuteron spins into ring plane and let them freely precess.
2. Lock the solenoid RF phase to the polarization direction of the ensemble
3. Use small RF solenoid amplitude to mimic polarization buildup

- During commissioning, waveguide RF Wien filter will be rotated to observe RF phase-dependence with small amplitudes

Volker Hejny, Ed Stephenson

Phase-locking now works via changing of the COSY RF (first try). Later, we will phase-lock to RF Wien filter RF.
Outline

- Introduction
- Recent Achievements
  - Spin coherence time
  - Spin tune measurement
  - Study of magnetic machine imperfections
- Technical challenges
- Toward a first direct $p, d$ EDM measurement
- Conclusion
## Timeline: Stepwise approach towards all-in-one machine

<table>
<thead>
<tr>
<th>Step</th>
<th>Aim / Scientific goal</th>
<th>Device / Tool</th>
<th>Storage ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Spin coherence time studies</td>
<td>Horizontal RF-B spin flipper</td>
<td>COSY</td>
</tr>
<tr>
<td></td>
<td>Systematic error studies</td>
<td>Vertical RF-B 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 $10^{-27} \text{e} \cdot \text{cm}$</td>
<td>RF $\vec{E} \times \vec{B}$ Wien filter</td>
<td>Modified COSY</td>
</tr>
<tr>
<td>3</td>
<td>Built dedicated all-in-one ring for $p, d, ^3\text{He}$</td>
<td>Common magnetic-electrostatic deflectors</td>
<td>Dedicated ring</td>
</tr>
<tr>
<td>4</td>
<td>EDM measurement of $p, d, ^3\text{He}$ at $10^{-29} \text{e} \cdot \text{cm}$</td>
<td></td>
<td>Dedicated ring</td>
</tr>
</tbody>
</table>

**Time scale:**

- Steps 1 and 2: $< 5$ years
- Steps 3 and 4: $> 5$ years
JEDI Collaboration

• **JEDI = Jülich Electric Dipole Moment Investigations**

  ![JEDI logo](image)

  *May the force be with us!*

• ~100 members (Aachen, Dubna, Ferrara, Indiana, Ithaka, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St Petersburg, Stockholm, Tbilisi, … [http://collaborations.fz-juelich.de/ikp/jedi/](http://collaborations.fz-juelich.de/ikp/jedi/))

• ~ 10 PhD students
Conclusion

- EDMs offer new window to disentangle sources of $CP$ violation, and to explain matter-antimatter asymmetry of the universe.
- First direct EDM measurements $(p, d)$ at COSY $(10^{-27} \text{ e} \cdot \text{cm}) < 2019$
- Development of a dedicated EDM storage ring $(10^{-29} \text{ e} \cdot \text{cm})$
  - Conceptual design report 2019
- Spin tune determination is a new precision tool for accelerator studies
  - Map out magnetic imperfections in a machine
- Successful phase-locking of spin precession to solenoid RF
- Development of high-precision spin tracking tools, incl. RF structures.
- Development of electrostatic deflectors (also $E_r \times B_y$), BPMs etc.

Very challenging ..., but the physics is fantastic.
Georg Christoph Lichtenberg (1742-1799)

“Man muß etwas Neues machen, um etwas Neues zu sehen.”
“You have to make (create) something new, if you want to see something new”
Publications

Experiment:


Theory: