Electric Dipole Moment Measurements at Storage Rings

J. Pretz
RWTH Aachen & FZ Jülich

PSI, March 2015
Introduction: Electric Dipole Moments (EDMs):
What is it?
Why is it interesting?
What do we know about EDMs?

Experimental Method:
How to measure charged particle EDMs?

Results of first test measurements:
Spin Coherence time and Spin tune
What is it?
Electric Dipoles

Classical definition:

\[ \vec{d} = \sum_{i} q_i \vec{r}_i \]
### Order of magnitude

<table>
<thead>
<tr>
<th></th>
<th>atomic physics</th>
<th>hadron physics</th>
</tr>
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<tbody>
<tr>
<td>charges</td>
<td>$e$</td>
<td></td>
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<tr>
<td>$</td>
<td>\vec{r}_1 - \vec{r}_2</td>
<td>$</td>
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<tr>
<td>EDM</td>
<td></td>
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<td>naive expectation</td>
<td>$10^{-8} e \cdot \text{cm}$</td>
<td></td>
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<tr>
<td>observed</td>
<td>water molecule</td>
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<td>$10^{-13} e \cdot \text{ cm}$</td>
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<tr>
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<td>water molecule</td>
<td>neutron</td>
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<tr>
<td></td>
<td>$2 \cdot 10^{-8} e \cdot \text{ cm}$</td>
<td>$&lt; 3 \cdot 10^{-26} e \cdot \text{ cm}$</td>
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</table>
neutron EDM of $d_n = 3 \cdot 10^{-26}$ e·cm corresponds to separation of $u$– from $d$–quarks of $\approx 5 \cdot 10^{-26}$ cm
Operator $\vec{d} = q\vec{r}$

is odd under parity transformation ($\vec{r} \rightarrow -\vec{r}$):

$$\mathcal{P}^{-1}\vec{d}\mathcal{P} = -\vec{d}$$

Consequences:
In a state $|a\rangle$ of given parity the expectation value is 0:

$$\langle a|\vec{d}|a\rangle = -\langle a|\vec{d}|a\rangle$$

but if $|a\rangle = \alpha|P = +\rangle + \beta|P = -\rangle$

in general $\langle a|\vec{d}|a\rangle \neq 0 \Rightarrow$ i.e. molecules
EDM of molecules

ground state: mixture of

\[ \psi_s = \frac{1}{\sqrt{2}} (\psi_1 + \psi_2), \quad P = + \]
\[ \psi_a = \frac{1}{\sqrt{2}} (\psi_1 - \psi_2), \quad P = - \]
Order of magnitude

**Molecules** can have large EDM because of degenerated ground states with different parity.
Molecules can have large EDM because of degenerated ground states with different parity

Elementary particles (including hadrons) have a definite parity and cannot posses an EDM
\[ P|\text{had} \> = \pm 1|\text{had} \> \]
Molecules can have large EDM because of degenerated ground states with different parity.

Elementary particles (including hadrons) have a definite parity and cannot possess an EDM

\[ P|\text{had} > = \pm 1|\text{had} > \]

unless

\[ \mathcal{P} \text{ and time reversal } T \text{ invariance are violated!} \]
$\vec{d}$: EDM
$\vec{\mu}$: magnetic moment
both $\parallel$ to spin

$$H = -\mu \vec{\sigma} \cdot \vec{B} - d \vec{\sigma} \cdot \vec{E}$$

$\mathcal{T}$: $H = -\mu \vec{\sigma} \cdot \vec{B} + d \vec{\sigma} \cdot \vec{E}$

$\mathcal{P}$: $H = -\mu \vec{\sigma} \cdot \vec{B} + d \vec{\sigma} \cdot \vec{E}$

$\Rightarrow$ EDM measurement tests violation of fundamental symmetries $\mathcal{P}$ and $\mathcal{T}(\Leftrightarrow \mathcal{CP})$
Symmetries in Standard Model

<table>
<thead>
<tr>
<th></th>
<th>electro-mag.</th>
<th>weak</th>
<th>strong</th>
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</thead>
<tbody>
<tr>
<td>$C$</td>
<td>✓</td>
<td>⌚</td>
<td>✓</td>
</tr>
<tr>
<td>$\mathcal{P}$</td>
<td>✓</td>
<td>⌚</td>
<td>(✓)</td>
</tr>
<tr>
<td>$\mathcal{CPT} \rightarrow \mathcal{CP}$</td>
<td>✓</td>
<td>(✓)</td>
<td>(✓)</td>
</tr>
</tbody>
</table>

- $C$ and $\mathcal{P}$ are maximally violated in weak interactions (Lee, Yang, Wu)
- $\mathcal{CP}$ violation discovered in kaon decays (Cronin,Fitch) described by CKM-matrix in Standard Model
- $\mathcal{CP}$ violation allowed in strong interaction but corresponding parameter $\theta_{QCD} \lesssim 10^{-10}$ (strong $\mathcal{CP}$-problem)
Sources of $\mathcal{CP}$–Violation

<table>
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<tr>
<th>Standard Model</th>
</tr>
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<tbody>
<tr>
<td><strong>Weak interaction</strong></td>
</tr>
<tr>
<td>CKM matrix</td>
</tr>
<tr>
<td><strong>Strong interaction</strong></td>
</tr>
<tr>
<td>$\theta_{QCD}$</td>
</tr>
<tr>
<td><strong>beyond Standard Model</strong></td>
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<tr>
<td>e.g. SUSY</td>
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Why is it interesting?
Matter-Antimatter Asymmetry

Excess of matter in the universe:

\[ \eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \]

<table>
<thead>
<tr>
<th></th>
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<th>SM prediction</th>
</tr>
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<tbody>
<tr>
<td>( \eta )</td>
<td>( 6 \times 10^{-10} )</td>
<td>( 10^{-18} )</td>
</tr>
</tbody>
</table>

Sakharov (1967): \( CP \) violation needed for baryogenesis

⇒ New \( CP \) violating sources beyond SM needed to explain this discrepancy

They could manifest in EDMs of elementary particles
What do we know about EDMs?
EDM: Current Upper Limits

- Electron (YbF, ThO)
- Muon
- Tau
- Neutron (Hg)
- Proton ($\Lambda$)
- Deuteron

$\text{edm/e cm} \times 10^n$

- $10^{-39}$
- $10^{-37}$
- $10^{-35}$
- $10^{-33}$
- $10^{-31}$
- $10^{-29}$
- $10^{-27}$
- $10^{-25}$
- $10^{-23}$
- $10^{-21}$
- $10^{-19}$
- $10^{-17}$
- $10^{-15}$

- Standard Model ($\theta_{QCD}=0$)
- SUSY ($\frac{\alpha}{\pi} < \varphi_{CP} < 1$)

- FZ Jülich: EDMs of charged hadrons: $p, d, \Lambda, \text{He}_3$
EDM: Current Upper Limits

FZ Jülich: EDMs of charged hadrons: $p, d, ^3\text{He}$
Why Charged Particle EDMs?

- no direct measurements for charged hadrons exist
- potentially higher sensitivity (compared to neutrons):
  - longer life time,
  - more stored protons/deuterons
- complementary to neutron EDM:
  \[ d_d = d_p + d_n \Rightarrow \text{access to } \theta_{QCD} \]
- EDM of one particle alone not sufficient to identify \( CP \)-violating source
Sources of \( CP \) Violation

- Neutron, Proton
- Nuclei: \(^2\text{H}, ^3\text{H}, ^3\text{He}\)
- Diamagnetic atoms: Hg, Xe, Ra
- Paramagnetic atoms: Tl, Cs
- Molecules: YbF, ThO, HfF\(^+\)
- Leptons: muon
- Quark EDM
- Quark chromo-EDM
- Gluon chromo-EDM
- Four-quark operators
- Lepton-quark operators
- Lepton EDM

J. de Vries
How to measure charged particle EDMs?
Experimental Method: Generic Idea

For all EDM experiments (neutron, proton, atoms, ...):

Interaction of $\vec{d}$ with electric field $\vec{E}$

For charged particles: apply electric field in a storage ring:

\[
\frac{d\vec{s}}{dt} \propto d\vec{E} \times \vec{s}
\]

In general:

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

build-up of vertical polarization $s_\perp \propto |d|$
Experimental Requirements

- high precision storage ring (alignment, stability, field homogeneity)
- high intensity beams ($N = 4 \cdot 10^{10}$ per fill)
- polarized hadron beams ($P = 0.8$)
- large electric fields ($E = 10$ MV/m)
- long spin coherence time ($\tau = 1000$ s),
- polarimetry (analyzing power $A = 0.6$, acc. $f = 0.005$)

\[
\sigma_{\text{stat}} \approx \frac{1}{\sqrt{Nf\tau PAE}} \Rightarrow \sigma_{\text{stat}}(1\text{year}) = 10^{-29} \text{e} \cdot \text{cm}
\]

challenge: get $\sigma_{\text{sys}}$ to the same level
Systematics

Major source:
Radial $B$ field mimics an EDM effect:

- Difficulty: even small radial magnetic field, $B_r$ can mimic EDM effect if $\mu B_r \approx dE_r$
- Suppose $d = 10^{-29} \text{e} \cdot \text{cm}$ in a field of $E_r = 10\text{MV/m}$
- This corresponds to a magnetic field:
  $$B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22} \text{eV}}{3.1 \cdot 10^{-8} \text{eV/T}} \approx 3 \cdot 10^{-17} \text{T}$$

Solution: Use two beams running clockwise and counter clockwise, separation of the two beams is sensitive to $B_r$
Sensitivity needed: $1.25 \text{ fT}/\sqrt{\text{Hz}}$ for $d = 10^{-29} \text{ e cm}$ (possible with SQUID technology)
Spin Precession: Thomas-BMT Equation

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{e}{m}[G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right) \vec{v} \times \vec{E} + \frac{m}{e\gamma}d(\vec{E} + \vec{v} \times \vec{B})] \times \vec{s}$$

$\Omega$: angular precession frequency  
$d$: electric dipole moment  
$G$: anomalous magnetic moment  
$\gamma$: Lorentz factor
Spin Precession: Thomas-BMT Equation

\[ \frac{\mathbf{d}s}{\mathbf{d}t} = \bar{\Omega} \times \mathbf{s} = \frac{e}{m}[G\mathbf{B} + \left(G - \frac{1}{\gamma^2 - 1}\right) \mathbf{v} \times \mathbf{E} + \frac{m}{e} d (\mathbf{E} + \mathbf{v} \times \mathbf{B})] \times \mathbf{s} \]

\( \bar{\Omega} \): angular precession frequency  
\( d \): electric dipole moment  
\( G \): anomalous magnetic moment  
\( \gamma \): Lorentz factor

dedicated ring: pure electric field, 
freeze horizontal spin motion \( \left( G - \frac{1}{\gamma^2 - 1}\right) = 0 \)
Spin Precession: Thomas-BMT Equation

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

**Ω**: angular precession frequency  
**d**: electric dipole moment  
**G**: anomalous magnetic moment  
**γ**: Lorentz factor

**COSY**: pure magnetic ring
access to EDM via motional electric field \(\vec{v} \times \vec{B}\), 
requires additional radio-frequency \(E\) and \(B\) fields 
to suppress \(G\vec{B}\) contribution
\[ \frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{e}{m} \left( G\vec{B} + \frac{m}{es} d\vec{v} \times \vec{B} \right) \times \vec{s} \]

Problem:
Due to precession caused by magnetic moment, 50% of time longitudinal polarization component is \( \parallel \) to momentum, 50% of the time it is anti-\( \parallel \).

\[ \vec{E}^* = \vec{v} \times \vec{B} \]

\[ \vec{s} \]
\[ \vec{p} \]

E* field in the particle rest frame tilts spin due to EDM up and down \( \Rightarrow \) no net EDM effect.
\[ \frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{e}{m} \left( G\vec{B} + \frac{m}{es} d\vec{v} \times \vec{B} \right) \times \vec{s} \]

Problem:
Due to precession caused by magnetic moment, 50% of time longitudinal polarization component is \( \parallel \) to momentum, 50% of the time it is anti-\( \parallel \).

\[
\vec{E}^* = \vec{v} \times \vec{B}
\]

\( \vec{s} \rightarrow \vec{p} \)

> 50% \( \dot{s}_d = \otimes 

< 50% \( \dot{s}_d = \odot 

\( E^* \) field in the particle rest frame tilts spin due to EDM up and down \( \Rightarrow \) no net EDM effect

Use resonant “magic Wien-Filter” in ring \( (\vec{E}_W + \vec{v} \times \vec{B}_W = 0) \):

\( E^*_W = 0 \rightarrow \) part. trajectory is not affected but

\( B^*_W \neq 0 \rightarrow \) mag. mom. is influenced

\( \Rightarrow \) net EDM effect can be observed!
Spin Precession: Thomas-BMT Equation

\[
\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{e}{m}[G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E} + \frac{m}{es}d(\vec{E} + \vec{v} \times \vec{B})] \times \vec{s}
\]

\(\vec{\Omega}\): angular precession frequency
\(d\): electric dipole moment
\(G\): anomalous magnetic moment
\(\gamma\): Lorentz factor

**COSY:**

- pure magnetic ring
- access to EDM via motional electric field \(\vec{v} \times \vec{B}\)
- requires additional radio-frequency \(E\) and \(B\) fields to suppress \(G\vec{B}\) contribution

neglecting EDM term

spin tune: \(\nu_s \approx \left|\frac{\vec{\Omega}}{\omega_{cyc}}\right| = \gamma G\), \(\left(\vec{\omega}_{cyc} = \frac{e}{\gamma m} \vec{B}\right)\)
Results of first test measurements
COSY provides (polarized) protons and deuterons with $p = 0.3 - 3.7\text{GeV/c}$

⇒ Ideal starting point for charged particle EDM searches
R & D at COSY

- maximize spin coherence time (SCT)
- precise measurement of spin precession (spin tune)
- rf- Wien filter design and construction
- tests of electro static deflectors (goal: field strength > 10 MV/m)
- development of high precision beam position monitors
- polarimeter development
- spin tracking simulation tools
Experimental Setup

- Inject and accelerate vertically polarized deuterons to $p \approx 1 \text{ GeV/c}$
Experimental Setup

- Inject and accelerate vertically polarized deuterons to $p \approx 1 \text{ GeV/c}$
- flip spin with help of solenoid into horizontal plane
Experimental Setup

- Inject and accelerate vertically polarized deuterons to $p \approx 1 \text{ GeV/c}$
- Flip spin with help of solenoid into horizontal plane
- Extract beam slowly (in 100 s) on target
- Measure asymmetry and determine spin precession
Asymmetry Measurements

Detector signal \( N_{up,dn} \propto (1 \pm P A \sin(\gamma G_{rev} t)) \)

\[ A_{up, dn} = \frac{N_{up} - N_{dn}}{N_{up} + N_{dn}} = P A \sin(\gamma G_{rev} t) = P A \sin(\nu s n_{\text{turn}}) \]

\( A \): analyzing power, \( P \): polarization

\[ A_{up, dn} = 0 \]

\[ A_{up, dn} = PA \]
Polarimetry

Cross Section & Analyzing Power for deuterons

\[ N_{up, dn} \propto (1 \pm PA \sin(\nu_s f_{rev} t)) \]

\[ A_{up, dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} \]
\[ = PA \sin(\nu_s f_{rev} t) \]
\[ = PA \sin(\nu_s n_{turn}) \]

\( A \): analyzing power
\( P \): beam polarization
Polarimeter

elastic deuteron-carbon scattering

Up/Down asymmetry $\propto$ horizontal polarization $\rightarrow \nu_s = \gamma G$

Left/Right asymmetry $\propto$ vertical polarization $\rightarrow d$

$$N_{up, dn} \propto 1 \pm PA \sin(\nu_s n_{turn}), \quad f_{rev} \approx 750 \text{ kHz}$$
Results: Spin Coherence Time (SCT)

Short Spin Coherence Time

unbunched beam

$\Delta p/p = 10^{-5} \Rightarrow \Delta \gamma/\gamma = 2 \cdot 10^{-6}$, $T_{rev} \approx 10^{-6}$ s

$\Rightarrow$ decoherence after $< 1$ s

cooled bunched beam eliminates 1st order effects in $\Delta p/p$

$\Rightarrow$ SCT $\tau = 20$ s
Results: Spin Coherence Time (SCT)

**Long Spin Coherence Time**

![Graph showing horizontal asymmetry run 2051 with values for \( \chi^2 \), amplitude, and SCT.]

Using correction sextupole to correct for higher order effects leads to SCT of \( \tau = 400 \text{ s} \).
Spin Tune $\nu_s$

Spin tune: $\nu_s = \gamma G = \frac{\text{nb. of spin rotations}}{\text{nb. of particle revolutions}}$

deuterons: $p_d = 1 \text{ GeV/c} \ (\gamma = 1.13), \ G = -0.14256177(72)$

$\Rightarrow \nu_s = \gamma G \approx -0.161$
Spin Tune $\nu_s$ measurement

- Problem: detector rate $\approx 5$ kHz, $f_{rev} = 750$kHz
  - $\Rightarrow$ only 1 hit every 25th period
- Not possible to use usual $\chi^2$-fit
- Use unbinned Maximum Likelihood (under investigation)

![Graph showing the distribution of events over turn numbers](image)
Spin Tune $\nu_s$ measurement

- map all events into first period ($T = 1/(\nu_s f_{rev}) \approx 8\mu s$) and perform $\chi^2$-fit (requires knowledge of $\nu_s f_{rev}$)
- Analysis is done in macroscopic time bins of $10^6$ turns ($\approx 1.3$ s)
Asymmetry in 1st period

Preliminary only works if $T_s = \frac{1}{\nu_s f_{rev}}$ is correct.
allows for $\sigma_{\nu_s} \approx 10^{-6}$

now fix $\nu_s$ at maximum and look at phase vs. turn number
phase is determined for turn intervals of $10^6$ turns
Phase Measurements

$10^6$ turns

1st derivative gives deviation from assumed spin tune
Phase Measurements

$10^6$ turns

1st derivative gives deviation from assumed spin tune

phase

turn nb., time

1st derivative gives deviation from assumed spin tune
\[ \nu_s(n) = \nu_s^0 + \frac{1}{2\pi} \frac{d\phi}{dn} \]
Results: Spin Tune $\nu_s$

![Graph showing the relationship between time [s] and number of particle turns [10^6], with angular displacement $\phi$ on the y-axis and time on the x-axis. The data points are marked with small + symbols.](image-url)
Results: Spin Tune $\nu_S$

\[ \hat{\phi} [\text{rad}] \]
\begin{align*}
\phi &\sim 2.5 \\
3 &\sim 3.5
\end{align*}

\[ \Delta \nu_s [10^{-9}] \]
\begin{align*}
0 &\sim 50 \\
-50 &\sim 0
\end{align*}
Results: Spin Tune $\nu_s$

time [s]

$\bar{\phi}$ [rad]

$\Delta \nu_s [10^{-9}]$

$\Delta \nu_s [10^{-9}]$

number of particle turns $[10^6]$
Spin Tune Measurement

- precision of spin tune measurement $10^{-10}$ in one cycle
- spin rotation due to electric dipole moment:
  \[ \nu_s = \frac{vm\gamma d}{es} = 5 \cdot 10^{-11} \text{ for } d = 10^{-24} \text{ e cm} \]
  (in addition rotations due to $G$ and imperfections)
- Compare to muon $g - 2$: $\sigma_{\nu_s} \approx 3 \cdot 10^{-8}$ per year
- main difference: measurement duration $600\mu s$ compared to $100 s$
- spin tune measurement can now be used as tool to investigate systematic errors
Spin Tune as tool to investigate systematics

$$\nu_s = \gamma G + \text{imperfections kicks}$$

- Create artificial imperfections with solenoids/steerers
- measure spin tune change $\Delta \nu_s$
- expectation
  $$\Delta \nu_s \propto (y_\pm - a_\pm)^2$$
  $a_\pm$: kicks due to imperfections,
  $y_\pm$: kicks due to solenoids
Spin Tune jumps

\[ \Delta v_s = 3.01072(66) \times 10^{-6} \]
parabolic behavior expected from simulations

\[ \beta = \frac{\chi_1 \pm \chi_2}{2}, \chi_{1,2}: \text{solenoid strength} \]

for perfect machine, minimum should be at \( y^+ = 0 \)
parabolic behavior expected from simulations

\[ y_\pm = \chi_1 \pm \chi_2 \]

\[ \Delta \nu_s (y_- = \text{const}) \]

\[ y_- = 9.25 \text{ mrad} \]

\[ y_- = 3.7 \text{ mrad} \]

parabolic behavior expected from simulations

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

\( \chi_{1,2} \): solenoid strength

for perfect machine, minimum should be at \( y^+ = 0 \)
JEDI Collaboration

- **JEDI** = Jülich Electric Dipole Moment Investigations
- ≈ 100 members
  (Aachen, Daejeon, Dubna, Ferrara, Grenoble, Indiana, Ithaca, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, ...)
- ≈ 10 PhD students
Storage Ring EDM Efforts

Common R&D work
- Spin Coherence Time
- BPMs
- Spin Tracking
- Polarimetry
- electric fields
- ...

BNL
- all electric ring (p)

Jülich
- first direct measurement with upgraded COSY
- dedicated ring (p,d,³He)
EDMs of elementary particles are of high interest to disentangle various sources of $\mathcal{CP}$ violation searched for to explain matter - antimatter asymmetry in the Universe.

EDM of charged particles can be measured in storage rings.

Experimentally very challenging because effect is tiny.

First promising results from test measurements at COSY:

- Spin coherence time: few hundred seconds
- Spin tune precision: $10^{-10}$ in one cycle
Spare
Electron and Neutron EDM

J. M. Pendlebury & E.A. Hinds,
NIMA 440(2000) 471
EDM: SUSY Limits

electron:
MSSM: \( \varphi \approx 1 \Rightarrow d = 10^{-24} - 10^{-27} \, \text{e}\cdot\text{cm} \)
\( \varphi \approx \alpha/\pi \Rightarrow d = 10^{-26} - 10^{-30} \, \text{e}\cdot\text{cm} \)

neutron:
MSSM: \( d = 10^{-24} \, \text{e}\cdot\text{cm} \cdot \sin \phi_{CP} \frac{200 \, \text{GeV}}{M_{SUSY}} \)
Electrostatic defectors from Fermilab (±125kV at 5 cm ≈ 5MV/m)

- large-grain Nb at plate separation of a few cm yields ≈ 20MV/m
Wien Filter

Conventional design
R. Gebel, S. Mey (FZ Jülich)

stripline design
D. Hölscher, J. Slim
(IHF RWTH Aachen)
2. Pure Electric Ring

Figure 3: An all-electric storage ring lattice for measuring the electric dipole moment of the proton. Except for having longer straight sections and separated beam channels, the all-in-one lattice of Fig. 1 is patterned after this lattice. Quadrupole and sextupole families, and tunes and lattice functions of the all-in-one lattice of Fig. 1 will be quite close to those given for this lattice in reference[3]. The match will be even closer with magnetic field set to zero for proton operation.

Brookhaven National Laboratory (BNL) Proposal
3. Combined $\vec{E}/\vec{B}$ ring

Figure 1: “All-In-One” lattice for measuring EDM’s of protons, deuterons, and helions.

Under discussion at Forschungszentrum Jülich (design: R. Talman)
### Summary of different options

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<thead>
<tr>
<th></th>
<th>Session 1</th>
<th>Session 2</th>
</tr>
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<tbody>
<tr>
<td>1.</td>
<td>pure magnetic ring (Jülich)</td>
<td>existing (upgraded) COSY ring can be used, shorter time scale</td>
</tr>
<tr>
<td>2.</td>
<td>pure electric ring (BNL)</td>
<td>no $\vec{B}$ field needed</td>
</tr>
<tr>
<td>3.</td>
<td>combined ring (Jülich)</td>
<td>works for $p, d, ^3\text{He}, \ldots$</td>
</tr>
</tbody>
</table>
EDM Activities Around the World

- Neutrons
  - ILL
  - ILL, @PNPI
  - PSI
  - FRM-2
  - RCNP, @TRIUMF
  - SNS
  - J-PARC

- Molecules
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - W@UMich
  - PbF@Oklahoma

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

- 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
  - FNAL
  - JPARC

  ~200

- Solids
  - GGG@Indiana
  - ferroelectrics@Yale

  ~10

K. Kirch
Systematics

Splitting of beams: \( \delta y = \pm \frac{\beta c R_0 B_r}{E_r Q_y^2} = \pm 1 \cdot 10^{-12} \text{ m} \)

\( Q_y \approx 0.1 \): vertical tune

Modulate \( Q_y = Q_y^0 (1 - m \cos(\omega_m t)) \), \( m \approx 0.1 \)

Splitting causes \( B \) field of \( \approx 0.4 \cdot 10^{-3} \text{ fT} \)

in one year: \( 10^4 \) fills of 1000 s \( \Rightarrow \sigma_B = 0.4 \cdot 10^{-1} \text{ fT per fill needed} \)

Need sensitivity \( 1.25 \text{ fT}/\sqrt{\text{Hz}} \)

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