Electric Dipole Moment Measurements at Storage Rings

J. Pretz
RWTH Aachen & FZ Jülich

Bonn, HISP, April 2014
Outline

- Introduction: Electric Dipole Moments (EDMs): What is it?
- Motivation: Why is it interesting?
- Experimental Method: How to measure charged particle EDMs?
- Results of first test measurements: Spin tune and Spin Coherence time
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>
</thead>
<tbody>
<tr>
<td>charges</td>
<td>$e$</td>
<td></td>
</tr>
<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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<tr>
<td>naive expectation</td>
<td>$10^{-8} e \cdot \text{cm}$</td>
<td></td>
</tr>
<tr>
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<td>water molecule</td>
<td>$2 \cdot 10^{-8} e \cdot \text{cm}$</td>
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<td>1 , \text{Å} = 10^{-8} \text{cm}</td>
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<tr>
<td>naive expectation</td>
<td>( 10^{-8} e \cdot \text{cm} )</td>
<td>( 10^{-13} e \cdot \text{cm} )</td>
</tr>
<tr>
<td>observed</td>
<td>water molecule</td>
<td>neutron</td>
</tr>
<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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</tbody>
</table>
neutron EDM of $d_n = 3 \cdot 10^{-26} \text{e}\cdot\text{cm}$ corresponds to separation of $u^-$ from $d^-$ quarks of $\approx 5 \cdot 10^{-26} \text{cm}$
Operator $\vec{d} = q\vec{r}$

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

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

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

$$\psi_s = \frac{1}{\sqrt{2}} (\psi_1 + \psi_2) \quad P = +$$

$$\psi_a = \frac{1}{\sqrt{2}} (\psi_1 - \psi_2) \quad P = -$$

(Cohen-Tannoudji, B. Diu, F. Laloë, Mécanique quantique)
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 possess an EDM:

\[ P|\text{had} > = \pm 1|\text{had} > \]
**Order of magnitude**

**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 unless \( \mathcal{P} \) and time reversal \( \mathcal{T} \) invariance are violated!
\( \mathcal{T} \) and \( \mathcal{P} \) violation of EDM

\( \vec{d} \): EDM  
\( \vec{\mu} \): magnetic moment  
both \( || \) 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 \( \mathcal{T} \) (\( \mathcal{CPT} \equiv \mathcal{CP} \))
**Symmetries in Standard Model**

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

- $C$ and $P$ 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)
Why is it interesting?
**Motivation: Sources of $CP$–Violation**

<table>
<thead>
<tr>
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<th>Standard Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weak interaction</strong></td>
<td>CKM matrix → unobservably small EDMs</td>
</tr>
<tr>
<td><strong>Strong interaction</strong></td>
<td>$\theta_{QCD}$ → best limit from neutron EDM</td>
</tr>
<tr>
<td>beyond Standard Model</td>
<td>e.g. SUSY → accessible by EDM measurements</td>
</tr>
</tbody>
</table>
Excess of matter in the universe:

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

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

Sakharov (1967): $\mathcal{CP}$ violation needed for baryogenesis

$\Rightarrow$ New $\mathcal{CP}$ violating sources beyond SM needed to explain this discrepancy

They could manifest in EDMs of elementary particles
What do we know about EDMs?
History of Neutron EDM

Year of Publication

Neutron EDM Upper Limit [em]

- ORNL, Harvard
- MIT, BNL
- LNPI
- Sussex, RAL, ILL

Supersymmetry Predictions

Standardmodel Predictions

EDM: Current Upper Limits

- Electron (YbF, ThO)
- Muon
- Tau
- Neutron
- Hg
- Proton

$\frac{\text{edm/e cm}}{-39 10^{39}} \leq \frac{\text{edm/e cm}}{-37 10^{37}} \leq \frac{\text{edm/e cm}}{-35 10^{35}} \leq \frac{\text{edm/e cm}}{-33 10^{33}} \leq \frac{\text{edm/e cm}}{-31 10^{31}} \leq \frac{\text{edm/e cm}}{-29 10^{29}} \leq \frac{\text{edm/e cm}}{-27 10^{27}} \leq \text{edm/e cm} \leq \frac{\text{edm/e cm}}{-25 10^{25}} \leq \frac{\text{edm/e cm}}{-23 10^{23}} \leq \frac{\text{edm/e cm}}{-21 10^{21}} \leq \frac{\text{edm/e cm}}{-19 10^{19}} \leq \frac{\text{edm/e cm}}{-17 10^{17}} \leq \frac{\text{edm/e cm}}{-15 10^{15}} = 0$

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

FZ Jülich: EDMs of charged hadrons: $p, d, ^3\text{He}$, $^1\text{H}$, $^1\text{H}$, $\Lambda$
EDM: Current Upper Limits

- Electron (YbF, ThO) $10^{-29}$
- Muon $10^{-29}$
- Tau $10^{-31}$
- Neutron $10^{-33}$
- Hg $10^{-35}$
- Proton (${}^{199}$Hg) $10^{-37}$

- Standard Model ($\alpha_{QCD} = 0$)
- SUSY ($\alpha / \pi < \varphi_{CP} < 1$)
- Precursor exp. at COSY ($10^{-24} e \cdot cm$)
- Dedicated ring ($10^{-29} e \cdot cm$)

FZ Jülich: EDMs of charged hadrons: $p, d, {}^{3}He$
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:
  \[ d_d \equiv d_p + d_n \Rightarrow \text{access to } \theta_{QCD} \]
- EDM of one particle alone not sufficient to identify \( C\overline{P} \)–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

QCD (including $\theta$-term)
- 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:

$$\frac{d\hat{s}}{dt} \propto d\vec{E} \times \hat{s}$$

In general:

$$\frac{d\hat{s}}{dt} = \vec{\Omega} \times \hat{s}$$

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 \( E = 10 \text{ MV/m} \)
- long spin coherence time \( \tau = 1000 \text{ s} \),
- polarimetry (analyzing power \( A = 0.6 \), acc. \( f = 0.005 \))

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

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 $E = 10 \text{MV/m}$
- 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 counterclockwise, separation of the two beams is sensitive to $B_r$
Sensitivity needed: $1.25 \text{fT/} \sqrt{\text{Hz}}$
(possible with SQUID technology)
Spin Precession: Thomas-BMT Equation

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

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

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

\( \vec{\Omega} \): 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}{eS}d(\vec{E} + \vec{v} \times \vec{B})] \times \vec{s}
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\(\Omega\): angular precession frequency  \(d\): electric dipole moment  
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**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}[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}
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\(\Omega\): angular precession frequency  \(d\): electric dipole moment  
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**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:  
\[\nu_s \approx \frac{|\vec{\Omega}|}{\omega_{rev}} = \gamma G\]
Spin Tune $\nu_s$

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

\[
\vec{s} \quad \vec{p} \quad 2\pi \gamma G
\]

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

$\Rightarrow \nu_s = \gamma G \approx -0.161$
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**
Experimental Setup

- Inject vertically polarized deuterons with $p \approx 1 \text{ GeV/c}$
- flip spin with help of solenoid into horizontal plane
- Extract beam slowly (in 100 s) on target
- Measure Polarization and spin precession
Polarimeter

elastic deuteron-carbon scattering
Up/Down asymmetry $\propto$ horizontal polarization $\rightarrow \nu_s = \gamma G$
Left/Right asymmetry $\propto$ vertical polarization $\rightarrow d$

$N_{up, dn} \propto 1 \pm PA \sin(\nu_s f_{rev} t), \quad f_{rev} \approx 781 \text{ kHz}$
Asymmetry Measurements

- Detector signal $N_{up, dn} \propto (1 \pm PA \sin(\gamma G f_{rev} t))$

$A_{up, dn} = \frac{N_{up} - N_{dn}}{N_{up} + N_{dn}} = PA \sin(\gamma G f_{rev} t)$

$A$: analyzing power, $P$: polarization

$A_{up, dn} = 0$

$A_{up, dn} = PA$
Polarimetry

Cross Section & Analyzing Power for deuterons

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

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

A : analyzing power
P : beam polarization
Spin Tune $\nu_s$ measurement

- Problem: detector rate $\approx 5$ kHz, $f_{\text{rev}} = 781$ kHz
  $\Rightarrow$ only 1 hit every 25th period
- not possible to use usual $\chi^2$-fit
- use unbinned Maximum Likelihood (under investigation)
Spin Tune $\nu_s$ measurement

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

\[
\chi^2 / \text{ndf} = 3.228 / 6 \\
\text{offset} = 0.1943 \pm 0.0167 \\
\text{amplitude } A = 0.2434 \pm 0.0236 \\
\text{phase } \phi = 3.569 \pm 0.096
\]

\[
2\pi \frac{t_s}{T_s} = \phi_s \text{ [rad]}
\]

• only works if \( T_s = \frac{1}{\nu_s f_{rev}} \) is correct.
set $\nu_s = \nu_{\text{max}}$ and determine phase in macroscopic time bins of $\approx 2s$
allows for $\sigma_{\nu_s} \approx 10^{-6}$
Phase Measurements

Phase measurements show deviations from the assumed spin tune.

The graph represents the phase measurements over time, indicating the deviation points.

[Graph showing phase measurements over time]
Phase Measurements

The diagram shows a series of phase measurements over time. The top graph represents the phase measurements, while the bottom graph shows the trend of phase deviation over time. The 1st derivative gives the deviation from the assumed spin tune.
Phase Measurements

1st derivative gives deviation from assumed spin tune
Results: Spin Tune $\nu_S$

Spin tune $\nu_S$ can be determined to $\approx 10^{-8}$ in 2 s

Average $\bar{\nu}_S$ in cycle ($\approx 100$ s) determined to $10^{-10}$

( for $G = 0$, $d = 10^{-24} \text{e} \cdot \text{cm} \Rightarrow \text{spin tune} = 5 \cdot 10^{-11}$ )
## Spin Tune $\nu_s$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Gedankenexperiment</th>
</tr>
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<tbody>
<tr>
<td>$G \approx -0.14, \ d \approx 0$</td>
<td>$G = 0, \ d = 10^{-24} \text{ e cm}$</td>
</tr>
<tr>
<td>$\nu_s = \gamma G = -0.16$</td>
<td>$\nu_s = \frac{vm\gamma d}{es} = 5 \cdot 10^{-11}$</td>
</tr>
</tbody>
</table>

Compare to $\sigma(\nu_s) = 10^{-10}$ in 100 s measurement
Results: Spin Coherence Time (SCT)

Short Spin Coherence Time

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

Horizontal Asymmetry Run: 2042

\[ \chi^2 / \text{ndf} = 69.29 / 90 \]

Amplitude \[ 0.282 \pm 0.006 \]

\[-\frac{1}{\text{SCT}} = -0.04968 \pm 0.00145 \]

Cooled bunched beam \( \Rightarrow \) SCT \( \tau = 20 \text{s} \)
Results: Spin Coherence Time (SCT)

**Long Spin Coherence Time**

Using correction sextupole to correct for higher order effects leads to SCT of $\tau = 400$ s
Results: Spin Coherence Time (SCT)

**Long Spin Coherence Time**

Using correction sextupole to correct for higher order effects leads to SCT of $\tau = 400$ s.
JEDI Collaboration

- **JEDI** = Jülich Electric Dipole Moment Investigations
- ≈ 100 members
  (Aachen, Dubna, Ferrara, Indiana, Ithaca, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, . . .)
- ≈ 10 PhD students
EDMs of elementary particles are of high interest to disentangle various sources of $CP$ violation searched for to explain matter - antimatter asymmetry in the Universe.

EDM of charged particles can be measured in storage rings.

Plans in Jülich: $10^{-24} \text{ e cm}$ at COSY

$10^{-29} \text{ e cm}$ with dedicated ring.

Experimentally very challenging because effect is tiny.

First promising results from test measurements at COSY.
Spare
Electron and Neutron EDM

J. M. Pendlebury & E.A. Hinds,
NIMA 440(2000) 471
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 Deflectors

- Electrostatic deflectors from Fermilab (±125kV at 5 cm \( \approx 5\text{MV/m} \))
- large-grain Nb at plate separation of a few cm yields \( \approx 20\text{MV/m} \)
Wien Filter

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

stripline design
D. Hölscher, J. Slim
(IHF RWTH Aachen)
1. Pure Magnetic Ring

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

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-\( \parallel \).

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

\( \vec{s} \) field in the particle rest frame tilts spin due to EDM up and down \( \Rightarrow \) no net EDM effect
1. Pure Magnetic Ring

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

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-\( \parallel \).

\( \vec{E}^* = \vec{v} \times \vec{B} \)

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

\( \vec{E}^* \) 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 (\( \vec{E} + \vec{v} \times \vec{B} = 0 \)):
\( E^* = 0 \rightarrow \) part. trajectory is not affected but
\( B^* \neq 0 \rightarrow \) mag. mom. is influenced

\( \Rightarrow \) net EDM effect can be observed!
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.
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)
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<table>
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<tbody>
<tr>
<td>1.) pure magnetic ring  (Jülich)</td>
<td>existing (upgraded) COSY ring can be used , shorter time scale</td>
<td>lower sensitivity</td>
</tr>
<tr>
<td>2.) pure electric ring  (BNL)</td>
<td>no $\vec{B}$ field needed</td>
<td>works only for $p$</td>
</tr>
<tr>
<td>3.) combined ring  (Jülich)</td>
<td>works for $p$, $d$, $^3$He, . . .</td>
<td>both $\vec{E}$ and $\vec{B}$ required</td>
</tr>
</tbody>
</table>
EDM Activities Around the World

- Neutrons
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC
  - ~200

- Molecules
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma
  - ~50

- 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
  - ~100

- Ions-Muons
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC
  - ~200

- Solids
  - GGG@Indiana
  - ferroelectrics@Yale
  - ~10

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

K. Kirch
Systematics

- Splitting of beams: \( \delta y = \pm \beta c R_0 B_r \frac{c R_0 B_r}{E_r Q_y^2} = \pm 1 \cdot 10^{-12} \text{ m} \)
- \( Q_y \approx 0.1 \): 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 \( \Rightarrow \sigma_B = 0.4 \cdot 10^{-1} \text{ fT per fill} \)
- Need sensitivity \( 1.25 \text{ fT}/\sqrt{\text{Hz}} \)

D. Kawall
Systematics