Measurement of **Electric Dipole Moments** of Charged Hadrons in Storage Rings

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Outline

Electric Dipole Moments (EDMs)

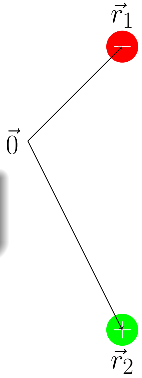
- What is it?
- Why is it interesting?
- What do we know about it?
- How to measure it?

What is it?

Electric Dipoles

Classical definition:

$$\vec{d} = \sum_i q_i \vec{r}_i$$



Order of magnitude

atomic physics:

$q_1 = -q_2 = e, \quad |\vec{r}_1 - \vec{r}_2| = 1\text{Å} = 10^{-10}\text{m}$

$$\rightarrow |\vec{d}| \;=\; 10^{-10} e \cdot \mathrm{cm}$$

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

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

hadron physics:

$|\vec{r}_1 - \vec{r}_2| = 1\,\mathrm{fm} = 10^{-13}$cm

$$\rightarrow |\vec{d}| \;=\; 10^{-13} e \cdot \mathrm{cm}$$

Limit on neutron EDM $< 3 \cdot 10^{-26} e\cdot$cm

Order of magnitude

- Molecules do have EDM of expected order of magnitude
- Hadrons not

Why?

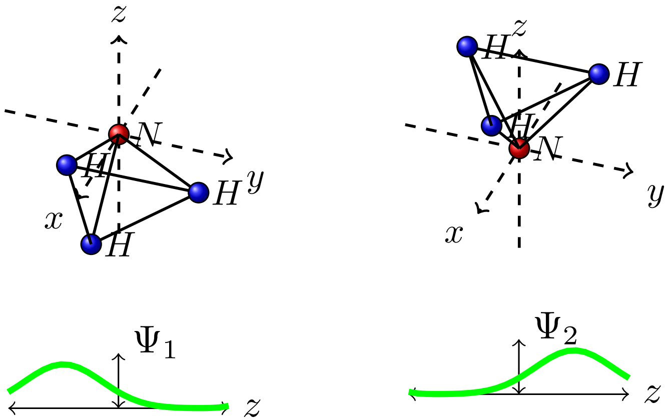
Hadrons have a given parity:
$P|\text{had}>= \pm 1|\text{had}>$
Operator: $\vec{d} = q\vec{r}$
is odd under parity transformation ($\vec{r} \to -\vec{r}$):

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

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

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

Situation is completely different for molecules



ground state: mixture of

$$\Psi_s = \frac{1}{\sqrt{2}}\left(\Psi_1 + \Psi_2\right) \quad P = +$$

$$\Psi_a = \frac{1}{\sqrt{2}}\left(\Psi_1 - \Psi_2\right) \quad P = -$$

(Cohen-Tannoudji, B. Diu, F. Laloë, Mécanique quantique)

Ground state is mixture of (allmost)* degenerated states with different parity:
$|a >= \alpha|\Psi_s > +\beta|\Psi_a >$

$\left\langle a|\vec{d}|a\right\rangle \neq 0$ in general

* energy difference $E_s - E_a$ can be neglected if energy shift due to applied electric field is large compared to $E_s - E_a$

Elementary particles (including hadrons) can only have dipole moment if parity $\mathcal{P}$ and time reversal $\mathcal{T}$ invariance are violated! (In this case they are not in a state of a given parity!)

$\mathcal{T}$ and $\mathcal{P}$ violation of EDM

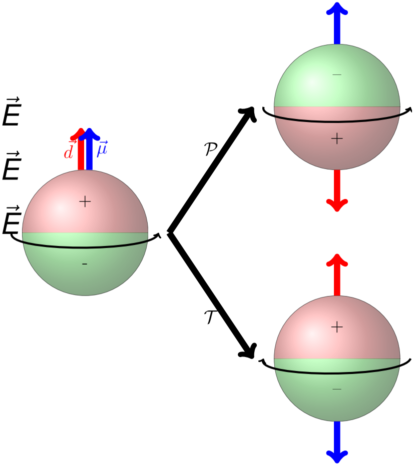
$\vec{d}$: EDM

$\vec{\mu}$: magnetic moment

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

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

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



$\mathcal{T}$ violation $\stackrel{\mathcal{CPT}}{\to}$ $\mathcal{CP}$ violation

Symmetries

Continious Symmetries

- Translation
- Rotation

Discrete Symmetries

- Parity ($\mathcal{P}$)
- Time Reversal ($\mathcal{T}$)
- Charge Conjugation ($\mathcal{C}$)

Symmetries

	electro-mag.	strong	weak
$\mathcal{C}$	$\checkmark$	$\checkmark$	$\lightning$
$\mathcal{P}$	$\checkmark$	$\checkmark$	$\lightning$
$\mathcal{T} \overset{CPT}{\rightarrow} \mathcal{CP}$	$\checkmark$	$\checkmark$	$(\lightning)$

- $\mathcal{C}$ and $\mathcal{P}$ are maximally violated in weak interactions (Lee, Young, Wu)
- $\mathcal{CP}$ violation discoverd in kaon decays (Cronin,Fitch)

Why is it interesting?

$\mathcal{CP}$ violation

- We are surounded by matter (and not anti–matter)
  $\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 10^{-10}$
- Starting from equal amount of matter and anti-matter at the Big Bang, from $\mathcal{CP}$-violation in Standard Model we expected only 10^{-18}
- In 1967 Sakharov formulated three prerequisites for baryogenesis. One of these is the combined violation of the charge and parity, $\mathcal{CP}$, symmetry.
- New $\mathcal{CP}$ violating sources outside the realm of the SM are clearly needed to explain this discrepancy of eight orders of magnitude.
- They could manifest in EDMs of elementary particles

Sources of $\mathcal{CP}$ violation

$\mathcal{CP}$ violation can have different sources

- Weak Interaction (unobservably small)
- QCD θ term (limit set by neutron EDM measurement)

  ——— Part of Standard Model ———
- sources beyond SM

$\Rightarrow$ It is important to measure neutron **and** proton **and** deuteron **and** ... EDMs in order to disentangle various sources of $\mathcal{CP}$ violation.

What do we know about (hadron) EDMs?

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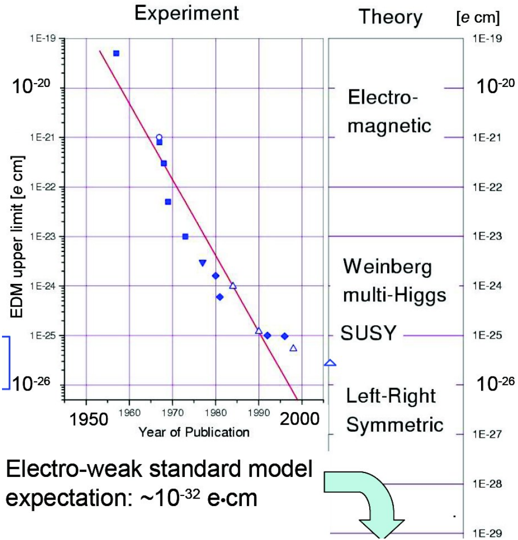
Particle/Atom	Current Limit/e·cm
Neutron	$< 3 \cdot 10^{-26}$
^{199}Hg	$< 3.1 \cdot 10^{-29}$
$\rightarrow$ Proton	$< 7.9 \cdot 10^{-25}$
Deuteron	?
^{3}He	?

- direct measurement only for neutron
- proton deduced from atomic EDM limit
- no measurement for deuteron (or other nuclei)

Why is there no measurement of charged particle EDMs?

- EDM of neutral particles can be measured in traps
- applying an electric field on a charged particle accelerates the particles, you have to build larger "traps" called **storage rings**
- Two exceptions:
  Λ: $< 1.5 \cdot 10^{-16} e{\cdot}\mathrm{cm}$
  μ: $0.1 \pm 0.9 \cdot 10^{-19} e{\cdot}\mathrm{cm}$

History of Neutron EDM



from K. Kirch

50 years of effort

Extensions of SM allow for large EDMs

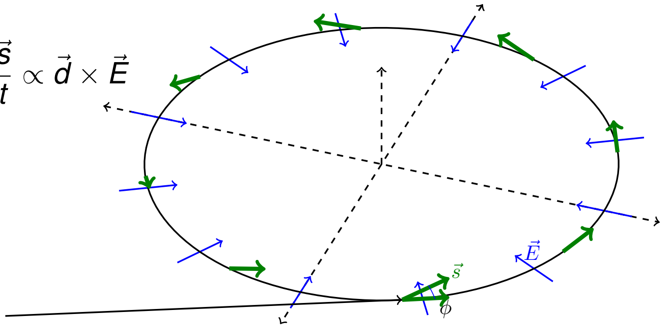
How to measure it?

How to measure it?

General Idea:

For **all** edm experiments (neutron, proton, atom, . . .):
Interaction of $\vec{d}$ with electric field $\vec{E}$
For charged particles: apply electric field in a storage ring:

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} \propto \vec{d} \times \vec{E}$$



Wait for build-up of vertical polarization $s_\perp \propto |d|$, then determine $s_\perp$ using polarimeter

In general: $\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s}$

“Thomas-BMT” formula

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

$\vec{d} = \eta\frac{e\hbar}{2mc}\vec{S}, \quad \vec{\mu} = 2(G+1)\frac{e\hbar}{2m}\vec{S}, \; G = \frac{g-2}{2}$, g:g−factor

Several Options:

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Several Options:

1. **Pure electric ring**
   with $\left(G - \frac{1}{\gamma^2 - 1}\right) = 0$, works only for $G > 0$

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   $G\vec{B} + \left(G - \frac{1}{\gamma^2-1}\right)\vec{v}\times\vec{E} = 0$
3. **Pure magnetic ring**

Required field strength

	$G = \frac{g-2}{2}$	p/GeV/c	E_R/MV/m	B_V/T
proton	1.79	0.701	10	0
deuteron	-0.14	1.0	-4	0.16
^{3}He	-4.18	1.285	17	-0.05

Ring radius $\approx$ 40m
Smaller ring size possible if $B_V \neq 0$ for proton

$$E = \frac{GBc\beta\gamma^2}{1 + G\beta^2\gamma^2}$$

1. Pure Electric Ring

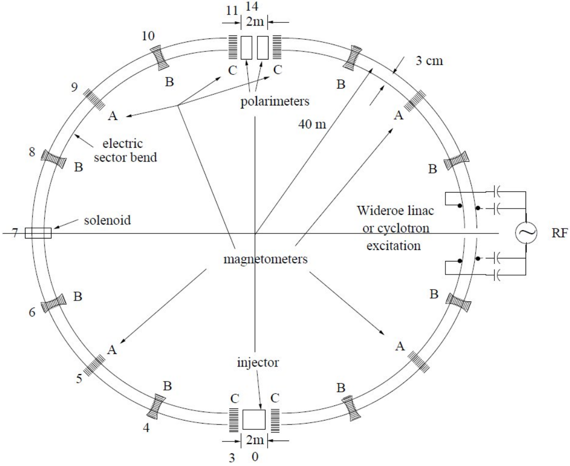


Figure 3: An all-electric storage ring lattice for measuring the electric dipole moment of the proton. Except for having longer straight sections and separated beam channels, the all-in-one lattice of Fig. 1 is patterned after this lattice. Quadrupole and sextupole families, and tunes and lattice functions 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

2. Combined $\vec{E}/\vec{B}$ ring

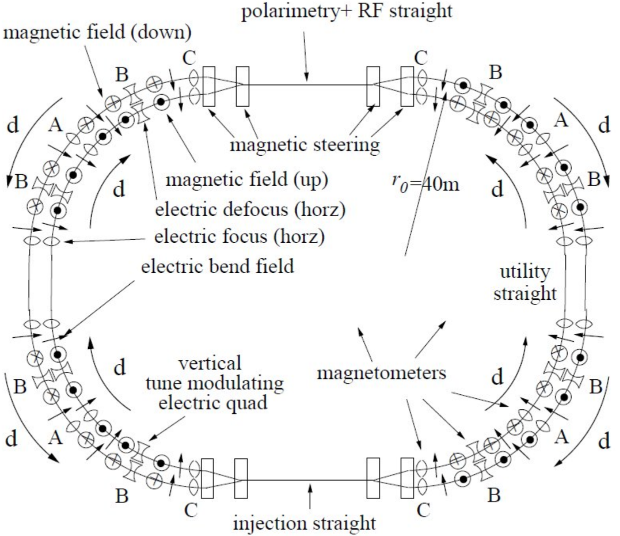


Figure 1: "All-In-One" lattice for measuring EDM's of protons, deuterons, and helions.

Under discussion in Jülich (design: R. Talman)

3. Pure Magnetic Ring

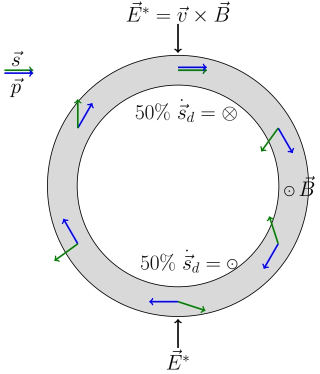
Main advantage:
Experiment can be performed at the existing (upgraded) COSY (COoler SYnchrotron) in Jülich on a shorter time scale!

COSY provides (polarized) protons and deuterons with $p = 0.3 - 3.7\text{GeV}/c \Rightarrow$ **Ideal starting point**

3. Pure Magnetic Ring

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

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



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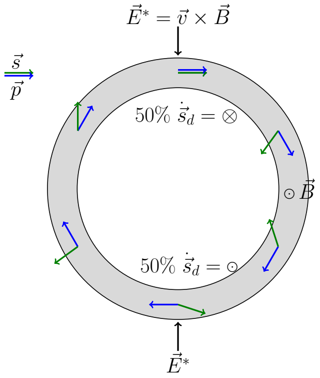

E^* field in the particle rest frame tilts spin due to EDM up and down
$\Rightarrow$ **no net EDM effect**

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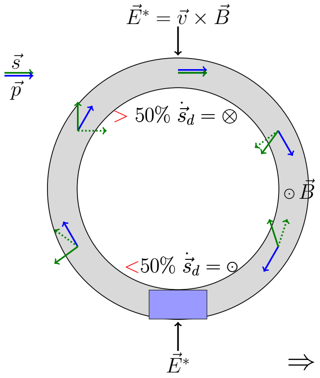

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Use resonant "magic Wien-Filter" in ring ($\vec{E} + \vec{v}\times\vec{B} = 0$):
$E^* = 0 \rightarrow$ part. trajectory is not affected but
$B^* \neq 0 \rightarrow$ mag. mom. is influenced

$\Rightarrow$ **net EDM effect can be observed!**

Summary of different options

	☺	☹
1.) pure electric ring (BNL)	no $\vec{B}$ field needed	works only for p
2.) combined ring (Jülich)	works for p, d, ^{3}He, ...	both $\vec{E}$ and $\vec{B}$ required
3.) pure magnetic ring (Jülich)	existing (upgraded) COSY ring can be used , shorter time scale	lower sensitivity

Statistical Sensitivity

$$\sigma \approx \frac{\hbar}{\sqrt{NfT\tau_p}PEA}$$

P	beam polarization	0.8
τ_p	Spin coherence time/s	1000
E	Electric field/MV/m	10
A	Analyzing Power	0.6
N	nb. of stored particles/cycle	4×10^7
f	detection efficiency	0.005
T	running time per year/s	10^7

$\Rightarrow \sigma \approx 10^{-29} e\cdot$cm/year (for magnetic ring $\approx 10^{-24} e\cdot$cm/year)
Expected signal $\approx$ 3nrad/s (for $d = 10^{-29} e\cdot$cm)
(BNL proposal)

Systematics

One 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 $d = 10^{-29} e \cdot \text{cm}$ in a field of $E = 10\text{MV/m}$
- This corresponds to a magnetic field:
  $$B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22} e\mathrm{V}}{3.1 \cdot 10^{-8} e\mathrm{V}/\mathrm{T}} \approx 3 \cdot 10^{-17}\mathrm{T}$$
  (Earth Magnetic field $\approx 5 \cdot 10^{-5}$ T)

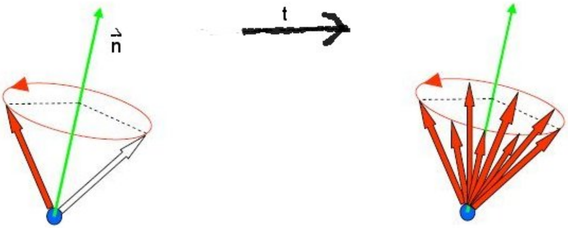
Solution: Use two beams running clockwise and counter clockwise, separation of the two beams is sensitive to B_r

Main Challenges

- Spin Coherence Time (SCT)$\approx$ 1000s
- Polarimetry on 1 ppm level (ppm = part per million)
- Beam positioning $\approx$ 10nm (relative between CW-CCW)
- Field Gradients $\approx$ 10MV/m

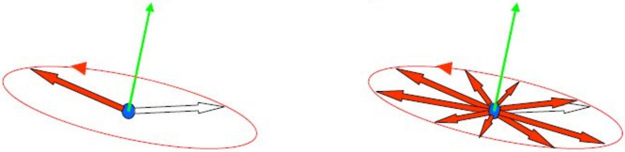
Spin Coherence Time (SCT)

Usally we dont care about decoherence of spins



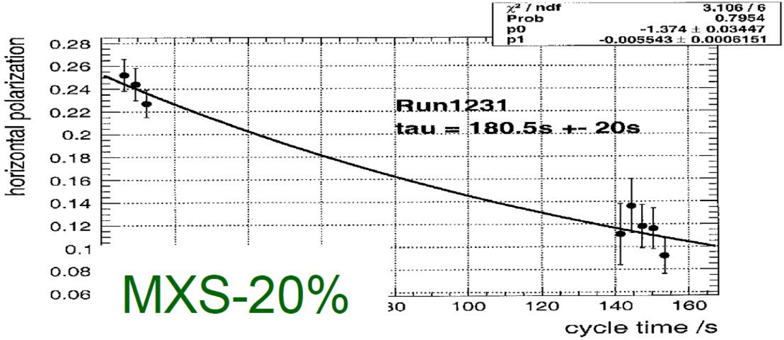
because polarisation with respect to invariant spin axis $\vec{n}$ is the same.

Situation is different if $\vec{S} \perp \vec{n}$



Longitudinal Polarization is lost.

Results on Spin Coherence Time (SCT)



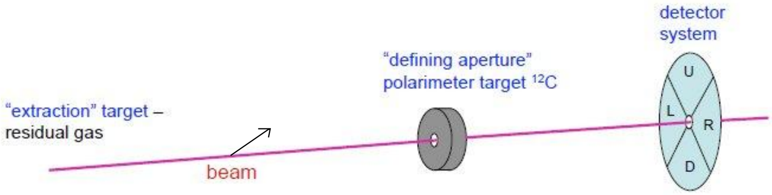
Spins decohere during storage time
very preliminary results form Cosy run May 2012 using correction sextupole

$\Rightarrow$ SCT increase from a few s to $\approx$ 200s already reached

(Ed. Stephenson)

Polarimeter

Principle: Particles hit a target:
Left/Right asymmetry gives information on EDM
Up/Down asymmetry gives information on g-2



Polarimeter: Figure of Merit

Goal: Determine vertical polarization P
Measure counting rates in left and right detector:

$$N_R \propto N^{up}\sigma_R + N^{dn}\sigma_L, \quad N_L \propto N^{up}\sigma_L + N^{dn}\sigma_R$$

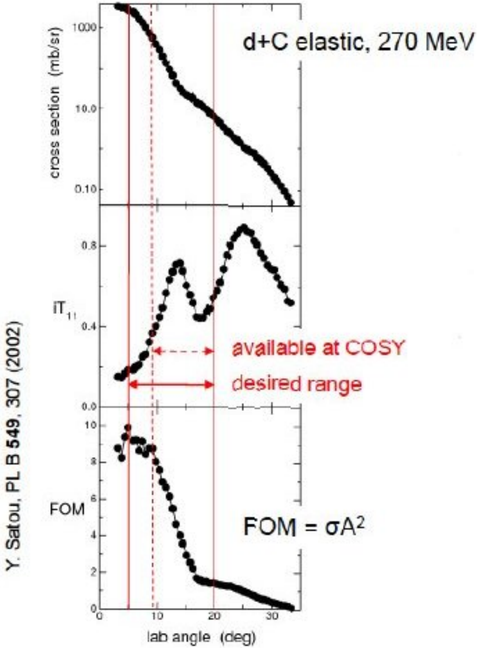
Calculate asymmetry:

$$\epsilon = \frac{N_R - N_L}{N_R + N_L} = \underbrace{\frac{N^{up} - N^{dn}}{N^{up} + N^{dn}}}_{P} \underbrace{\frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}}_{A} = P\,A$$

P : Polarization(to be determined), A : analyzing power(known)
$P = \frac{\epsilon}{A}$
Statistical error $\sigma_\epsilon = 1/\sqrt{N}$, $N = N_R + N_L$

$$\Rightarrow \sigma_P = \frac{1}{A\sqrt{N}}, \quad \text{Figure of merit (FOM)} = \frac{1}{\sigma_P^2} = A^2 N$$

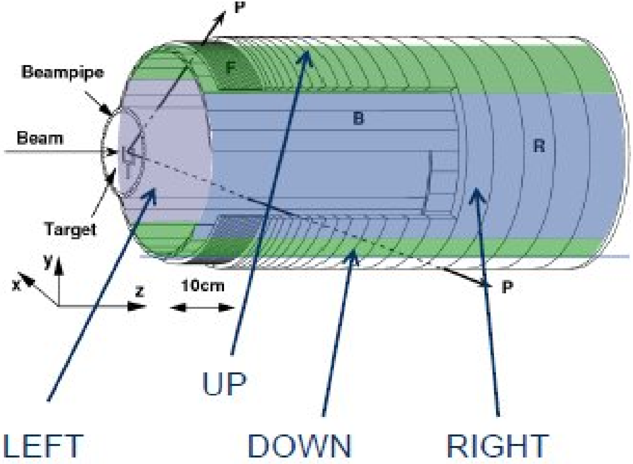
Polarimeter



Cross Section &
Analyzing Power
for deuterons

Polarimeter

Available at COSY for tests:
EDDA polarimeter



Stepwise approach of JEDI project in Jülich

JEDI = **J**ülich **E**lectric **D**ipole Moment **I**nvestigations

1	Spin coherence time studies Systematic Error studies	COSY
2	COSY upgrade first direct measurement at $10^{-24} e \cdot$ cm	COSY COSY
3	Build dedicated ring for p,d and ^{3}He	
4	EDM measurement at $10^{-29} e \cdot$ cm	Dedicated ring

Storage Ring EDM Efforts

Common R&D work

- Spin Coherence Time
- BPMs
- Spin Tracking
- Polarimetry
- ...

BNL

- all electric ring (p)

Jülich

- first direct measuremet with upgraded COSY
- all-in-one ring (p,d,^{3}He)

Summary

- EDM of various hadrons species are of high interest to disentangle various sources of $\mathcal{CP}$ violation searched for to explain matter - antimatter asymmetry in the Universe
- Up to now only direct measurement for neutron
- EDM of charged particles can be measured in storage rings
- Experimentally very challenging because effect is tiny
- Efforts at Brookhaven and Jülich to perform such measurements