Search for electric dipole moments in storage rings

JEDI Collaboration at FZ-Jülich

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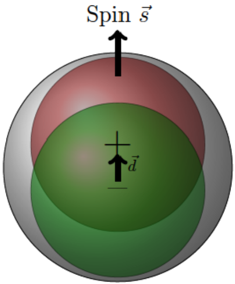
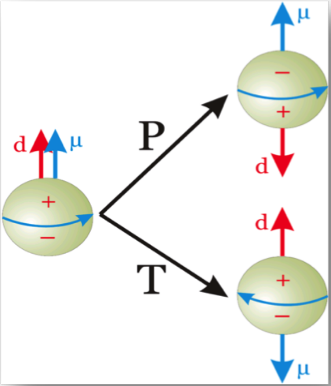
Electric Dipole Moments (EDM)



- Permanent separation of + and - charge
- Fundamental property of particles (like magnetic moment, mass, charge)
- Possible only via violation of time-reversal (T) and parity (P) symmetries
- *Nothing to do with electric dipole moments observed in some molecules (e.g. H_2O molecule)*

T and P violation of EDM



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

- T: $H = -\mu \frac{\vec{s}}{s} \cdot \vec{B} + d \frac{\vec{s}}{s} \cdot \vec{E}$
- P: $H = -\mu \frac{\vec{s}}{s} \cdot \vec{B} + d \frac{\vec{s}}{s} \cdot \vec{E}$

EDMs test violation of P and T symmetries ($\overset{CPT}{=}$ CP)

CP-violation & Matter-Antimatter Asymmetry

Matter dominance:

- Excess of Matter in the Universe:

	observed	SCM prediction
$\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma}$	6×10^{-10}	10^{-18}

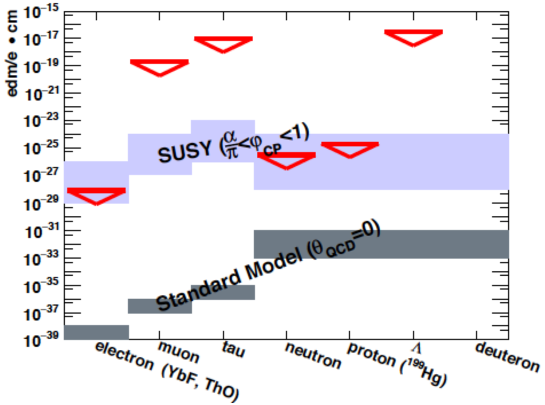
- Sacharov (1967): CP violation needed for baryogenesis

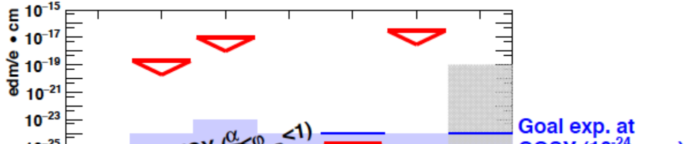
- $\Rightarrow$ New CP violating sources beyond SM needed to explain the discrepancy
- Could show up in EDMs of elementary particles

CP-violation & EDMs

Standard Model	
Weak interaction	
CKM matrix	→ unobservably small EDMs
Strong interaction	
θ_{QCD}	→ best limit from neutron EDM
beyond Standard Model	
e.g. SUSY	→ accessible by EDM measurements

EDM: Current upper limits



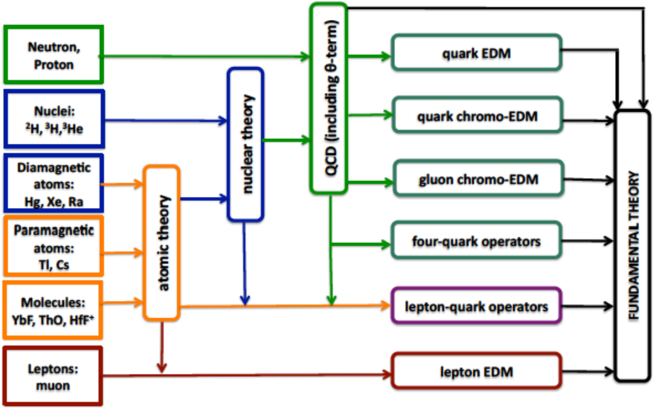


Why Charged Particle EDMs?

- No direct measurement for charged particle exist
- Potentially higher sensitivity (compared to neutrons):
  - longer lifetime;
  - more stored protons/deuterons
- complementary to neutron EDM:
  d_d, d_p, $d_n \Rightarrow$ access to θ_{QCD}

EDM of one particle not sufficient to identify CP-violating source

Sources of CP Violation

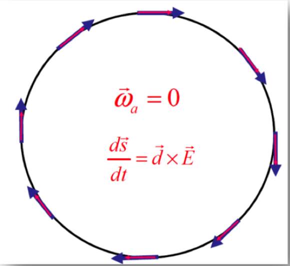


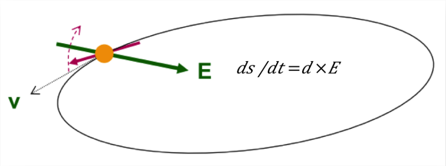
J. de Vries

Search for EDM in storage rings: concept

Procedure

1. Inject particles in storage ring
2. Align spin along momentum ($\rightarrow$ *freeze* horiz. spin-precession)
3. Search for time development of vertical polarization





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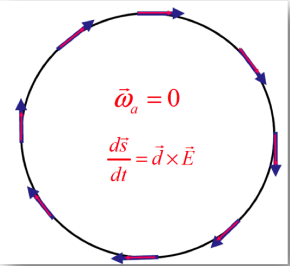
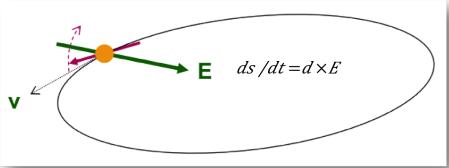




Frozen spin $\longrightarrow$ *electrostatic* ring (for p)

Requirements

Experiment

- High precision storage ring $\rightarrow$ **systematics** (alignment, stability, field homogeneity)
- High intensity beams (N=4 $\cdot$ 10^{10} per fill)
- Polarized hodron beams (P=0.8)
- Long spin coherence time (τ = 1000 s)
- Large electric fields (E = 10 MeV/m)
- Polarimetry (analyzing power A = 0.6, eff. = 0.005)

Statistics

$$\sigma_{stat} = \frac{\hbar}{\sqrt{Nf\tau PAE}} \Rightarrow \sigma_{stat}(1year) = 10^{-29} e \cdot cm$$

challenge: get σ_{sys} to the same level

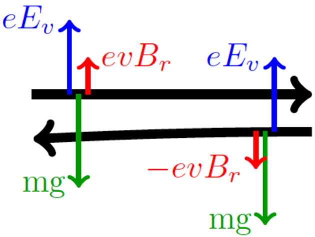
Systematics

Example: radial B field (B_r)

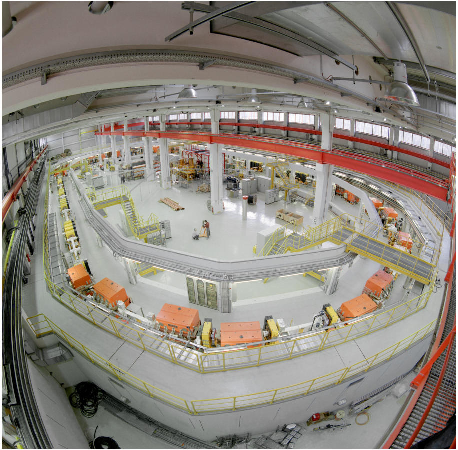
- B_r can mimic EDM (if $dE_r \approx \mu\, B_r$)
- E.g. $d = 10^{-29}$ e $\cdot$ cm, $E_r = 10$ MV/m
  - Corresponds to $B_r = \frac{dE_r}{\mu} \approx 10^{-17}\,T$

Solution

- Use of two beams running clockwise and counterclockwise
- Separation of the two beams sensitive to B_r



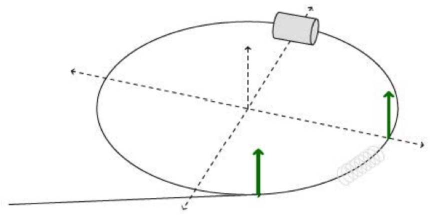
The COSY storage ring at FZ Jülich



Polarized protons and deuterons with p=0.3-3.7 GeV/c
$\Rightarrow$ **ideal starting point for charged particles EDM studies**

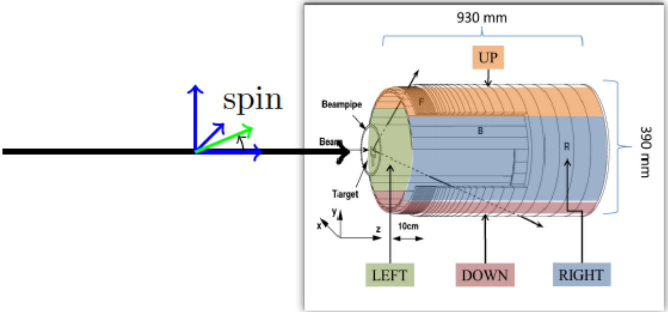
Experiment preparation

1. Inject and accelerate vertically pol. deut. to p $\approx$ 1 GeV/c
2. Flip spin with solenoid into horizontal plane
3. Extract beam slowly (100 s) on target
4. Measure asymmetry and determine spin precession



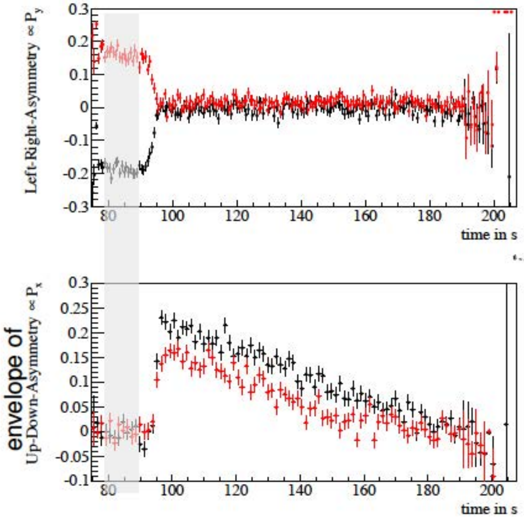
Polarimeter

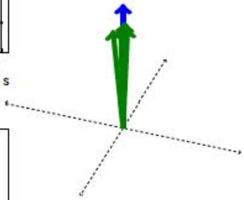
- Elastic deuteron-carbon scattering
- Up/Down asymmetry $\propto$ *horizontal polarization* $\rightarrow \nu_s = \gamma G$
- Left/Right asymmetry $\propto$ *vertical polarization* $\rightarrow$ d



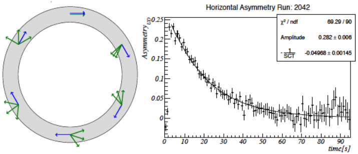
$N_{up,down} \propto 1 \pm P_{hor} A sen(\nu_s \omega_{rev} t)$, $f_{rev} \approx 750$ kHz

Polarization flip and *spin-coherence time*



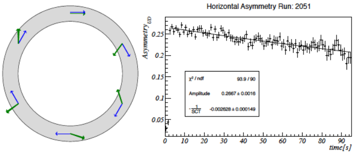


Spin-coherence time (SCT): developments



Short SCT

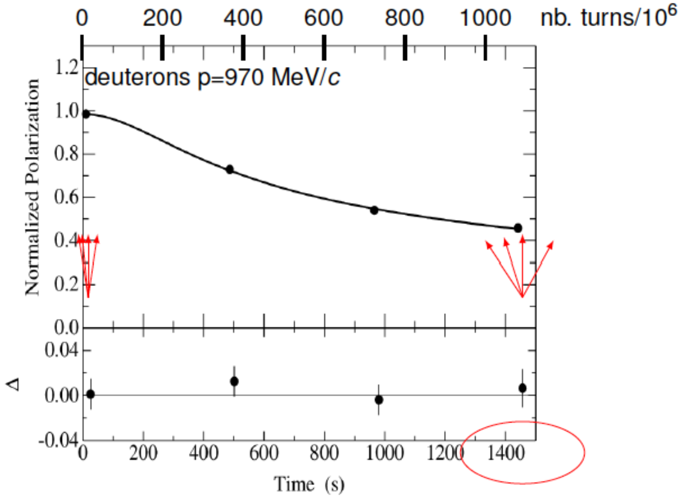
- Unbunched beam:
  - $\Delta p/p = 10^{-5}$
  - $\Rightarrow$ decoherence after < 1s
- Bunched beam:
  - No 1^{st} order effects in $\Delta p/p$
  - $\Rightarrow$ SCT = 20 s

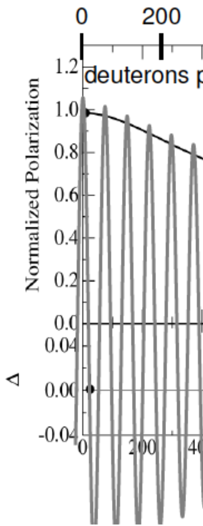


Long SCT

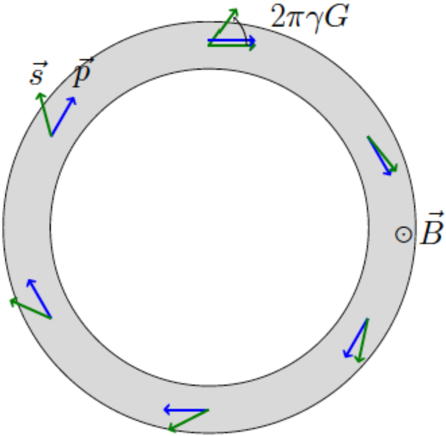
- Use of of 6-poles
  - Compensate for β oscillations

Spin-coherence time: results (τ_{SCT}> 1000 s)





Spin-tune: definition



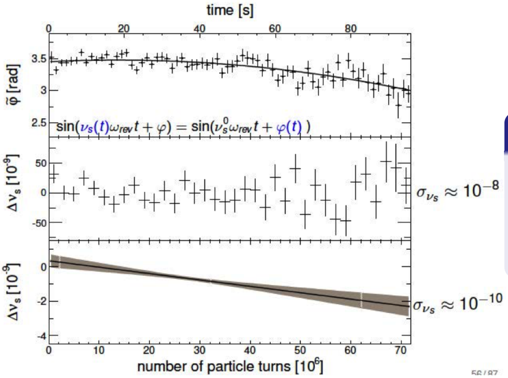
Spin-tune ν_s

$$\nu_s = \gamma G = \frac{nb.spin\!-\!rotations}{nb.particle\!-\!revolutions}$$

deuterons: p_d = 1 GeV/c (γ=1.13), G=-0.14256177

$$\Rightarrow \nu_s = \gamma G \approx -0.161$$

Spin-tune: results



Sensitivity

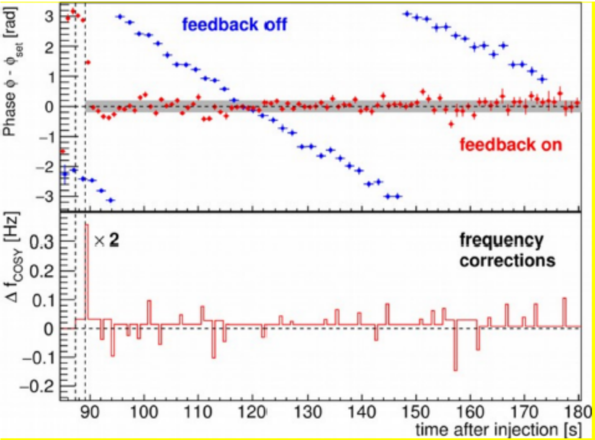
$\sigma(\nu_s = \gamma G) \approx 10^{-8}$ in 2 s

$\sigma(\nu_s = \gamma G) \approx 10^{-10}$ in 100 s

$\rightarrow \Delta\phi = 2\,\pi 10^{-10} = 0.6$ nrad

"Spin-feedback" system

Controlling 120kHz precession



References

1. Spin coherence time: τ_{SCT} > 1000 s
   - PRL 117, 054801 (2016)
2. Spin tune: $\bar{\nu}_s = -0.16097... \pm 10^{-10}$ in 100 s
   - PRL 115, 094801 (2015)
3. Spin-feedback: polarization vector kept within 12 degrees
   - PRL 119, 014801 (2017)

- 1.$\Rightarrow$ mandatory to reach statistical sensitivity
- 2. & 3. $\Rightarrow$ highly accurate measurement and manipulation of polarization vector

Proof of principle experiment using COSY

Highest sensitivity $\rightarrow$ new type of machine

- Electrostatic circular storage ring:
  - centripetal force produced primarily by electric fields.
  - E couples to EDM providing sensitivity ($< 10^{-29}$ e cm).
  - B means evil (μ large).

Proof-of-principle with novel RF Wien filter ($\vec{E} \times \vec{B}$)

- Magnetic machine: spins precess around stable spin axis ($\simeq$ direction of B-fields in dipole magnets).
- RF device at harmonic of spin-precession frequency:
  - $\Rightarrow$ *Phase lock* between spin precession and device RF.
  - $\Rightarrow$ Accumlate EDM effect vs time in cycle ($\sim$ 1000 s).

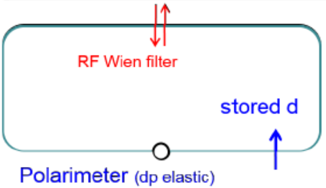
Goal of proof-of-principle experiment:

Show that SR can be used for a first direct EDM measurement.

RF Wien filter

A couple of remarks about the technique

- RF Wien filter avoids coherent betatron oscill. in the beam:
  - Lorentz force $\vec{F_L} = q(\vec{E} + \vec{v} \times \vec{B}) \simeq 0$.
  - EDM meas. mode $\vec{B} = (0, B_y, 0)$ and $\vec{E} = (E_x, 0, 0)$.



- deut. spin in the machine plane
- $d \neq 0 \rightarrow$ accumulation of vertical polarization P_y in $\tau_{SCT} \sim 1000$ s

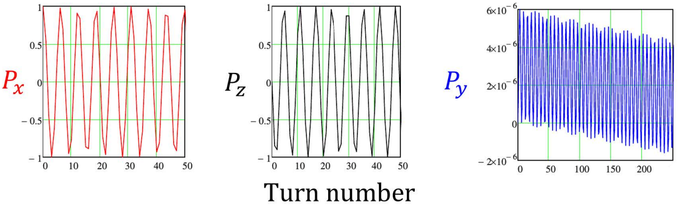
Statistical sensitivity

- In the range 10^{-23} to 10^{-24} e cm for deut. possible.
- Systematic effects: Alignment, magnetic imperfections of RF-Wien filter etc.,

$P_y(t)$ buildup using RF Wien filter for deuterons

Model calculation at beam momentum p_d = 970 MeV/c

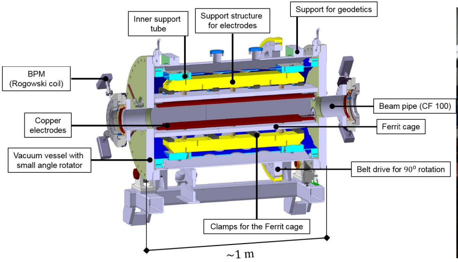
- G=-0.143, γ = 1.126, $f_s = |f_{rev}(\gamma G + K_{(=0)}|$ = 120.765 kHz
- Length of device: L_{WF}=1.55 m
- Assumed deuteron EDM: d=10^{-20} e cm
- Electric RF field: 1000 $\times E_{RF}$ = 2.145 $\times 10^6$ MV/m

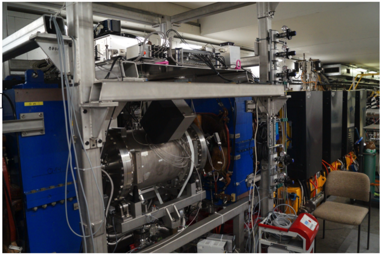


EDM effect accumulates in $P_y \propto$ d

Waveguide RF Wien filter

- Developed at FZJ in collaboration with RWTH-Aachen
- Installed in the PAX low-β section at COSY



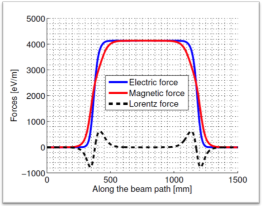


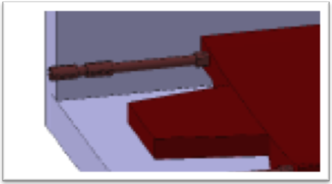
Aim: build the best possible device with respect to electromagnetic performance and mechanical tolerances

Lorentz force compensation

Integral Lorentz force of the order of - 3 eV/m

- Electric, magnetic and Lorentz forces in the WF
- Trapezoid electrodes determine crossing of E and B fields





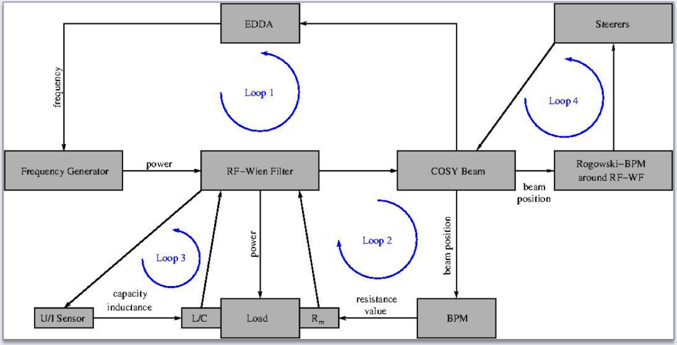
Lorentz force: $F_L = q(\vec{E} + \vec{v} \times \vec{B})$

- $\vec{v} = c(0, 0, \beta), \vec{E} = (E_x, E_y, E_z), \vec{B} = \mu_0(H_x, H_y, H_z)$
- $F_L = 0 \rightarrow E_x = -c \cdot \beta \cdot \mu_0 \cdot H_y \Rightarrow Z_q = \frac{E_x}{H_y} = c \cdot \beta \cdot \mu_0 \approx 173\Omega$

First commissioning run (June 2017)

Wien-filter control system

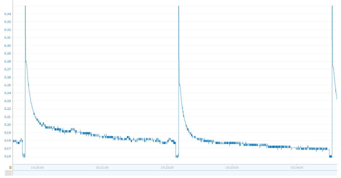
- Feedback loop(s) implementation and test



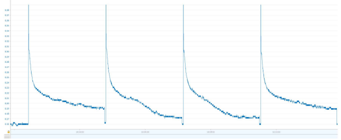
First commissioning run (June 2017)

Operation at 2.2 kW, E field vertical

- 3×10^8 protons in fill after acceleration and beam cooling
- E and B fields in phase & Z_q matched to $\beta \Rightarrow$ no beam loss



Z_q away from ideal ($173\ \Omega \rightarrow 403\ \Omega$) $\Rightarrow$ beam losses



Conclusions and Outlook

- EDMs $\rightarrow$ probes of CP-violating interactions
- Charged particle EDMs $\rightarrow$ new class of high-precision S.R.
- Feasibility studies ongoing at COSY
  - Important achievements already accomplished
  - First measurement of deuteron EDM in preparation
    - First results expected end 2018
- Project acknowledged with ERC-AdG "srEDM"
- Study group established at CERN:
  - Feasibility study of a (pure electrostatic) EDM proton ring

Thank you!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