Search for electric dipole moments of charged particles in storage rings

JEDI Collaboration

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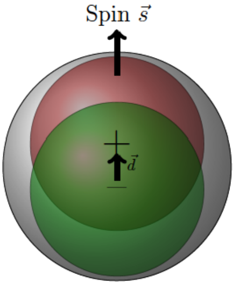
MENU-2019, June 07th 2019, Pittsburgh, Virginia

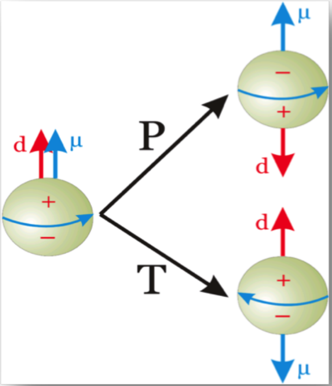
Motivation

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 $T \overset{CPT}{=} CP$ and parity P
- Nothing to do with EDMs of molecules (e.g. H_2O)
- connection to matter-antimatter asymmetry

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

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

CP-violation & Matter-Antimatter Asymmetry

Matter dominance:

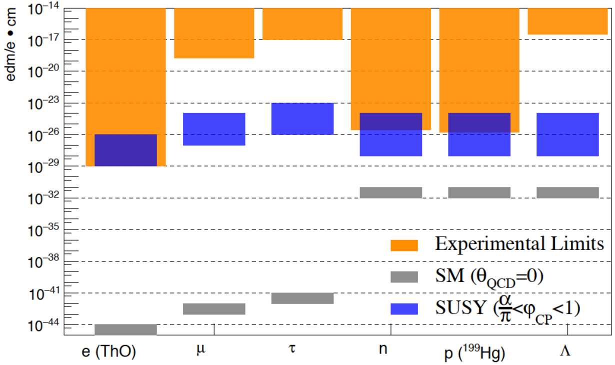
- Excess of Matter in the Universe:

	observed	SM 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-V sources beyond SM needed
- Could show up in EDMs of elementary particles

EDM: Current upper limits



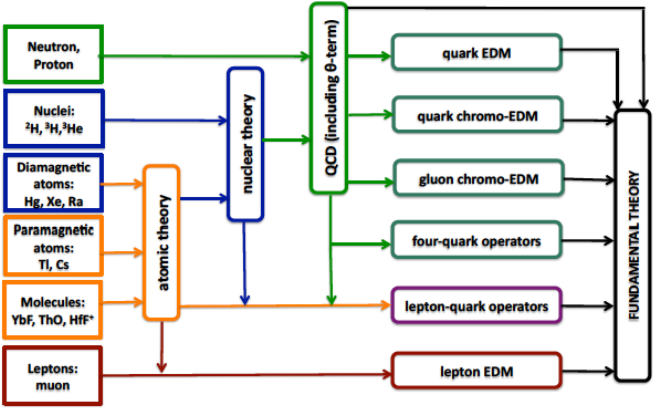
FZ Jülich: EDMs of charged hadrons: *p, d,* ^3He

Why Charged Particle EDMs?

- No direct measurement for charged hadron EDMs
- Potentially higher sensitivity (compared to neutrons):
  - longer lifetime;
  - more stored protons/deuterons
  - can apply larger electric fields in storage rings
- complementary to neutron EDM:

EDM of single particle not sufficient to identify CP-V source

Sources of CP Violation



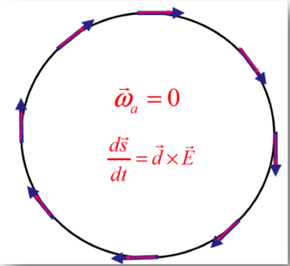
J. de Vries

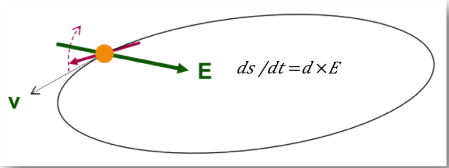
Experimental method

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





Spin Precession in a storage ring

Thomas-BMT equation

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[\underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}}_{=\Omega_{MDM}} + \underbrace{\frac{\eta}{2}\left(\vec{E} + \vec{v} \times \vec{B}\right)}_{=\Omega_{EDM}}\right] \times \vec{s}$$

- Mag. dip. mom. (MDM): $\vec{\mu} = 2(G+1)\frac{q\hbar}{2m}\vec{s}$ (G=1.79 for proton)
- El. dip. mom. (EDM): $\vec{d} = \eta\frac{q\hbar}{2mc}\vec{s}$ ($\eta = 2 \cdot 10^{-15}$ for d= $10^{-29} e \cdot cm$)

Frozen spin

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[\underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}}_{\Omega_{MDM}=0 \rightarrow \textbf{frozen spin}} + \frac{\eta}{2}\left(\vec{E} + \vec{v} \times \vec{B}\right)\right] \times \vec{s}$$

- Achievable with pure electric field for proton (G>0): $G = \frac{1}{\gamma^2 - 1}$
- Requires special combination of E, B fields and γ for d, ^3He (G<0)

Requirements

High precision, primarily electric storage ring

- Crucial role of alignment, stability, field homogeneity and shielding from magnetic fields.
- High beam intensity: N=4 $\cdot 10^{10}$ per fill
- Polarized hadron beams: P=0.8
- Long spin coherence time: τ = 1000 s
- Large electric fields: E = 10 MV/m
- Efficient polarimetry with:
  - large analyzing power: A = 0.6
  - high efficiency detection: eff. = 0.005

Expected statistical sensitivity in 1 year of DT:

- $\sigma_{stat} = \frac{\hbar}{\sqrt{Nf\tau}PAE} \Rightarrow \sigma_{stat} = 10^{-29} e \cdot cm$
- Experimentalist's goal: provide σ_{syst} to the same level.

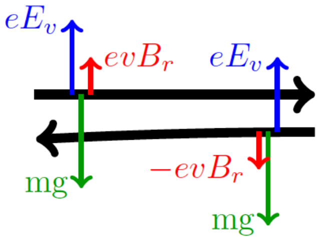
Systematics

Example: radial B field (B_r)

- B_r can mimic EDM (if $dE_r \approx \mu\, B_r$)
- E.g. $d = 10^{-29}$ e · 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

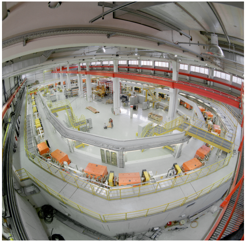


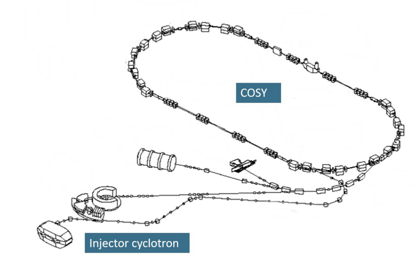
Achievements at COSY

The COSY storage ring at FZ-Jülich (Germany)

COoler SYnchrotron COSY

- Cooler and storage ring for (pol.) protons and deuterons.
- Momenta p= 0.3-3.7 GeV/c
- Phase-space cooled internal and extracted beams



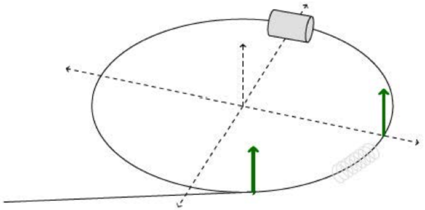


Formerly used as spin-physics machine for hadr. physics:

- Ideal starting point for srEDM related R&D
- First direct measurement of deuteron EDM

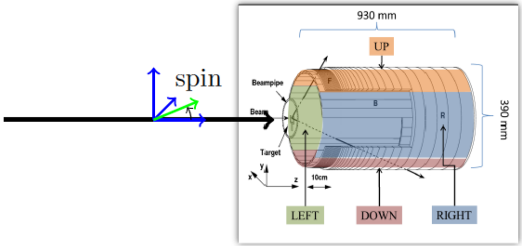
Experiment preparation

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

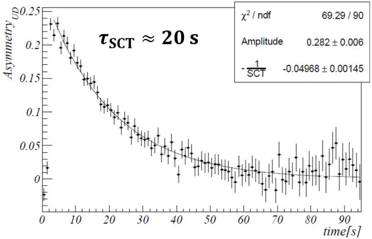
- Elastic deuteron-carbon scattering
- Up/Down asymmetry $\propto$ *horizontal polarization* $\rightarrow \nu_s = \gamma G$
- Left/Right asymmetry $\propto$ *vertical polarization* $\rightarrow$ d

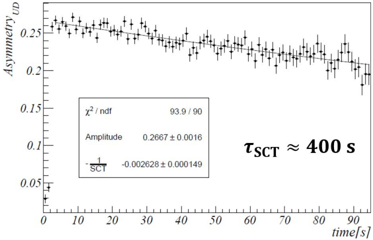


- Deut. at p = 1GeV/c: $\gamma = 1.13$ and $\nu_s = \gamma G \simeq$ - 0.161
- Spin-dependent differential cross section:

$N_{up,down} \propto 1 \pm \frac{3}{2} p_z A_y sin(\nu_s \omega_{rev} t)$, f_{rev} = 781 kHz

Optimization of spin-coherence time





2012: First result

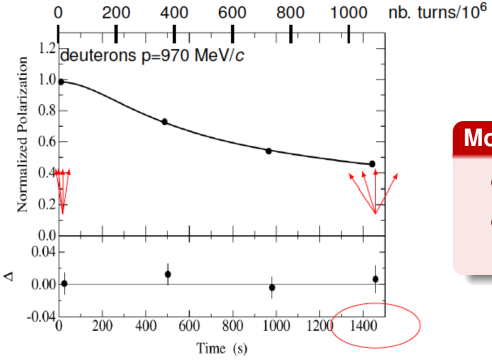
Exp. decay of asymmetry:

$$\epsilon_{UD} = \frac{N_D(t) - N_U(t)}{N_D(t) + N_U(t)}$$

2013: improvement

Use of 6-pole magnets to correct higher order effects: spin-coherence time increased

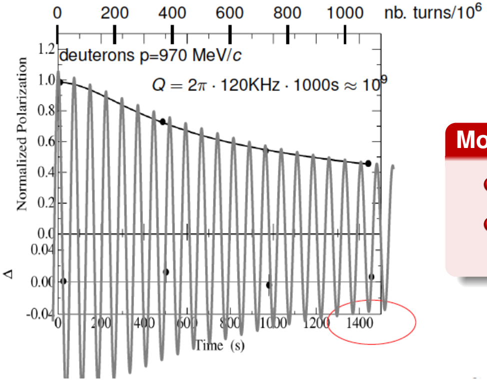
Optimization of spin-coherence time



More recent progress on τ_{SCT}

- τ_{SCT} = (782 ± 117)s
- Previously: τ_{SCT}(VEPP) ≈ 0.5 s (≈ 10^7 spin revolutions)

Optimization of spin-coherence time



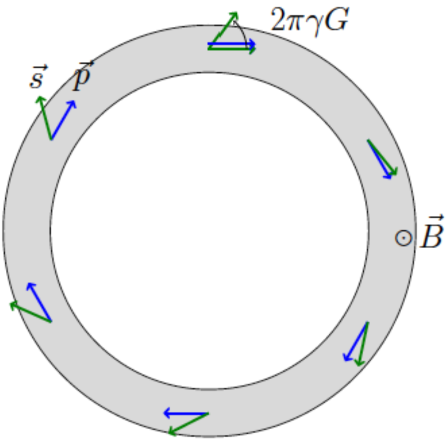
More recent progress on τ_{SCT}

- τ_{SCT} = (782 $\pm$ 117)s
- Previously: τ_{SCT}(VEPP) $\approx$ 0.5 s ($\approx 10^7$ spin revolutions)

Major achievement:

- About 10^9 stored deuterons.
- Long SCT was one of main obstacles of srEDM experiments.
- Large value of SCT of crucial importance, since $\sigma_{STAT} \propto \frac{1}{\tau_{SCT}}$

Spin-tune



Spin-tune ν_s

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

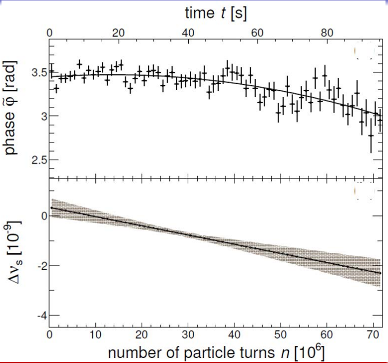
Stored deuterons at COSY

- p_d = 1 GeV/c (γ=1.13), G=-0.1425 $\Rightarrow \nu_s = \gamma G \approx -0.161$
- f_{rev} = 781 kHz $\Rightarrow f_s = \nu_s \times f_{rev} \approx$ 126 kHz

Precise determination of the spin-tune

Time stamping of events:

- Monitor phase of asymm. with fixed ν_s in 100 s: $\nu_s(n) = \nu_s^{fix} + \frac{1}{2\pi}\frac{d\tilde{\phi}}{dn} = \nu_s^{fix} + \Delta\nu_s(n)$



Experimental result:

- Interpolated spin tune in 100 s: $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$ ($\Delta\nu_s/\nu_s \approx 10^{-10}$)
  - Angle precision: $2\pi \times 10^{-10}$ = 0.6 nrad
  - Previous best: 3×10^{-8} per year (g-2 experiment)
- → new tool to study systematic effects in storage rings

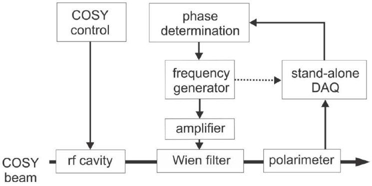
Phase locking spin precession in machine to device RF

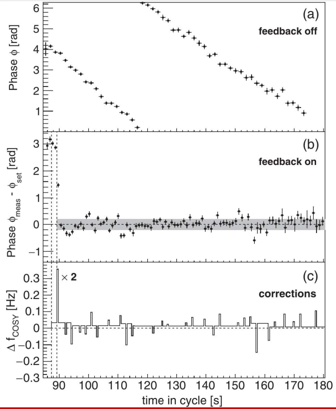
At COSY: freezing of spin precession not possible

→ phase-locking required to achieve precision for EDM

Spin-feedback system maintains:

- resonance frequency
- phase between spin-precession and device RF





Major achievement:

Error of phase-lock σ_ϕ = 0.21 rad

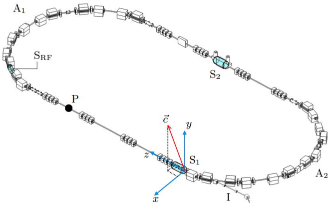
Study of machine imperfections

Precise experimental technique

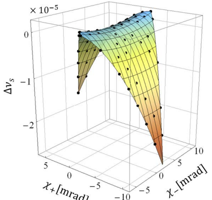
New method to investigate magnetic machine imperfections through accurate determination of spin-tune

Spin tune mapping

- Two solenoids act as spin rotators → generate artificial imperfection fields
- Measure spin-tune shifts vs spin kicks



- Saddle point determines tilt of stable spin axis by machine imperfections
- Control of background from MDM: $\Delta c = 2.8 \times 10^{-6}$ rad
- Systematics sensitivity for d-EDM: $\sigma_d \approx 10^{-20}$ e·cm



Towards a storage ring EDM measurement

Staged approach

Stage 1

precursor experiment

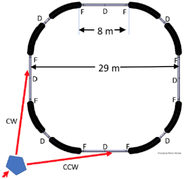
at COSY (FZ Jülich)

- magnetic storage ring

now

Stage 2

prototype ring

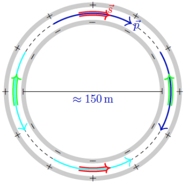


- electrostatic storage ring
- simultaneous ↻ and ↺ beams

5 years

Stage 3

dedicated storage ring



- magic momentum

(701 MeV/c)

10 years

$\sigma_{EDM}/(e \cdot \mathrm{cm})$

10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21} 10^{-22} 10^{-23} 10^{-24} 10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29}

Stage 1: proof of principle experiment using COSY

- Thomas - BMT equation for a *magnetic ring*:

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[\underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}}_{=\Omega_{MDM}} + \underbrace{\frac{\eta}{2}\left(\vec{E} + \vec{v} \times \vec{B}\right)}_{=\Omega_{EDM}}\right] \times \vec{s}$$

Storage rings: vertical B fields, radial E field

- MDM $\rightarrow$ fast spin precession in the horizontal plane
- EDM $\rightarrow$ slow vertical polarization buildup, up and down

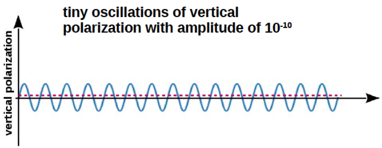
Access to EDM through motional E field

- Pure magnetic ring $\rightarrow$ motional electric field: $\vec{v} \times \vec{B}$
- $\Rightarrow$ access to EDM

RF-Wien filter

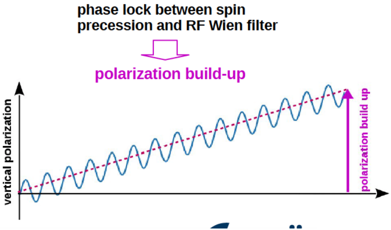
Magnetic ring

- Momentum $\uparrow\uparrow$ spin $\Rightarrow$ spin kicked up
- Momentum $\uparrow\downarrow$ spin $\Rightarrow$ spin kicked down
- $\Rightarrow$ no accumulation of vert. asymmetry



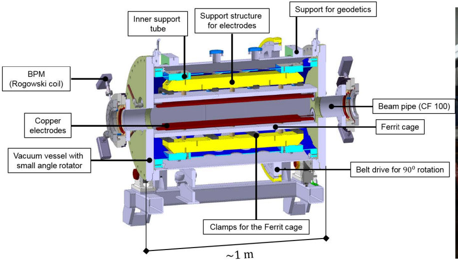
RF-Wien filter

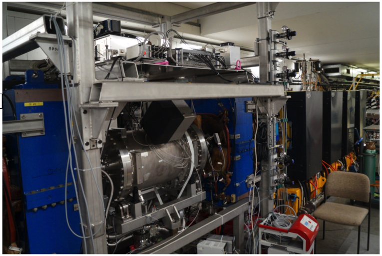
- Lorentz force: $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0$
- $\vec{B} = (0, B_y, 0)$ and $\vec{E} = (E_x, 0, 0)$



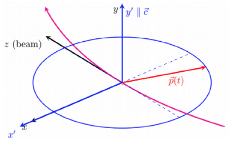
Waveguide RF Wien filter

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

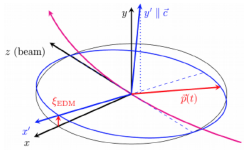




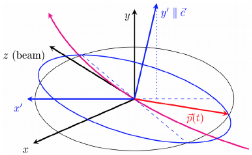
Effect of EDM on stable spin-axis



EDM absence



EDM effect



Magnetic misalignment

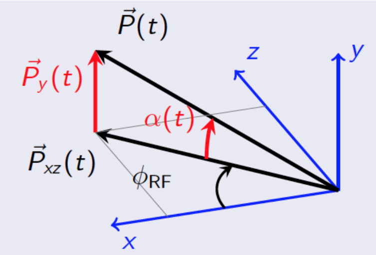
EDM tilts the stable spin-axis

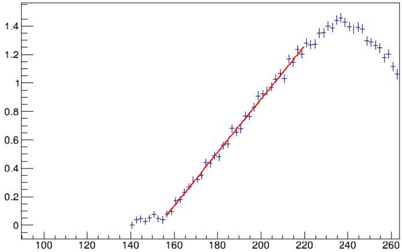
- Presence of EDM $\rightarrow \varepsilon_{EDM} > 0$
  - $\rightarrow$ spin precess around the $\vec{c}$ axis
  - $\rightarrow$ oscill. vert. polarization $p_y(t)$

Polarization buildup

Metod

- Wien filter operated with B normal to the ring plane
- Measurement of initial slopes of polarization buildup:
  - $\alpha(t) = \arctan\left(\frac{P_y}{P_{xy}}\right)$

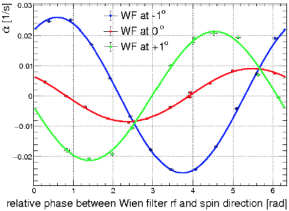




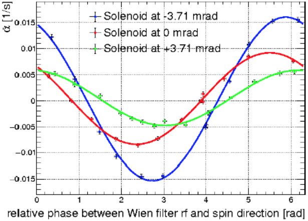
Measurement of EDM-like buildup signals

Rate out-of-plane angle $\dot{\alpha}(t)|_{t=0}$ as function of Wien filter RF phase ϕ_{RF}

- Variation of ϕ_{rot}^{WF} and χ_{rot}^{Sol1} affects the pattern of observed initial slopes $\dot{\alpha}$

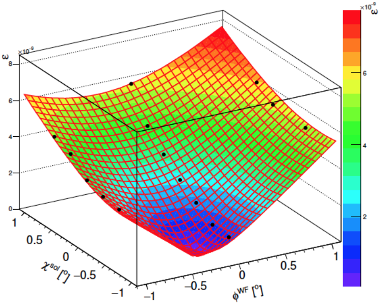


$\dot{\alpha}$ for $\phi_{\text{rot}}^{\text{WF}} = -1°, 0°, +1°$ and $\chi_{\text{rot}}^{\text{Sol 1}} = 0$.



$\dot{\alpha}$ for $\chi_{\text{rot}}^{\text{Sol 1}} = -1, 0, +1°$ and $\phi_{\text{rot}}^{\text{WF}} = 0$.

Preliminary results from run in Dec. 18



(f) First 16 points on the map.

Spin-tracking simulations necessary

- Orientation of stable spin axis at location of RF Wien filter including EDM determined by minimum of map
- Spin tracking simulation shall provide orientation of stable spin axis without EDM
- Second run foreseen in autumn 2019

Next steps

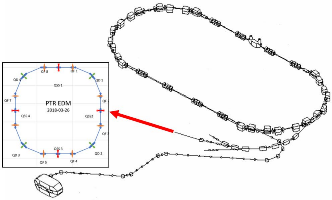
Stage 2: prototype EDM storage ring

Next step

- Build demonstrator for charged particle EDM
- Project prepared by CPEDM working group (CERN+JEDI+srEDM)
  - Physics Beyond Collider process (CERN)
  - European Strategy for Particle Physics Update
- Possible host sites: COSY or CERN

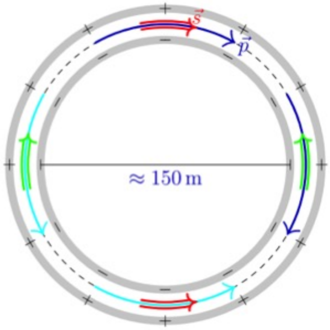
Scope of prototype ring of 100 m circumference

- p at 30 MeV all-electric CW-CCW beams operation
- p at 45 MeV frozen spin including additional vertical magnetic fields



- Storage time
- CW-CCW operation
- Spin-coherence time
- Polarimetry
- Magnetic moment effects
- Stochastic cooling
- pEDM measurement

Stage 3: precision EDM ring



500 m circumference ring

- All-electric deflection
- Magic momentum (p = 701 MeV/c)
- Simultaneous CW/CCW beams
- Phase-space cooled beams
- Long spin coherence time (> 1000 s)
- Non-destructive precision polarimetry
- Optimum orbit control
- Optimum shielding of external fields
- Control of residual (intentional) B_r field

"Holy Grail" of storage rings (largest ever conceived)

Conclusions

Search for charged particle EDMs (p, d, ^{3}He)

- EDMs $\rightarrow$ probes of CP-violating interactions
- Matter-antimatter asymmetry
- Measurements of different particles required

Investigations at COSY

- Important achievements accomplished
- First measurement of deuteron EDM ongoing
  - Results expected end 2019

Interest and acknowledgment

- Project acknowledged with ERC-AdG "srEDM"
- Study group established at CERN:
  - Design of a small-scale prototype ring
  - Feasibility study of a pure electrostatic EDM proton ring

JEDI Collaboration

JEDI = Jülich Electric Dipole Moment Investigations

- 140 members (Aachen, Daejeon, Dubna, Ferrara, Indiana, Ithaka, Julich, Krakow, Michigan, Minsk, Novosibirsk, St Petersburg, Stockholm, Tbilisi, ...)
- http://collaborations.fz-juelich.de/ikp/jedi

Summary