The search for electric dipole moments of charged particles using storage rings

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Motivation

Physics case

Problems

- Preponderance of matter over antimatter
- Nature of Dark Matter (DM)

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- Preponderance of matter over antimatter
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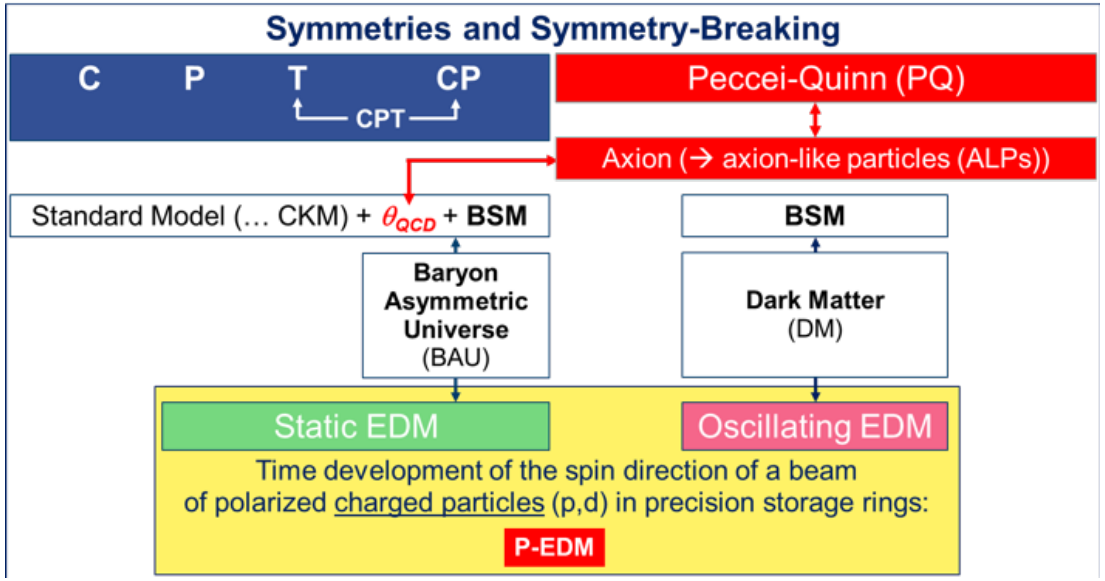
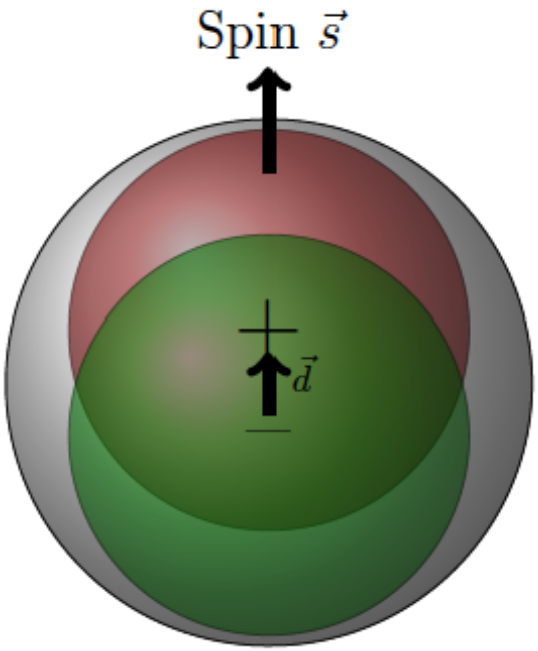
Approach

- Measurements of static Electric Dipole Moments (EDM) of fundamental particles.
- Searches for axion-like particles as DM candidates through oscillating EDM



Electric Dipole Moment (EDM)



- Permanent separation of + and - charge
- Fundamental property of particles (like magnetic moment, mass, charge)
- Possible via violation of time-reversal (T) and parity (P)

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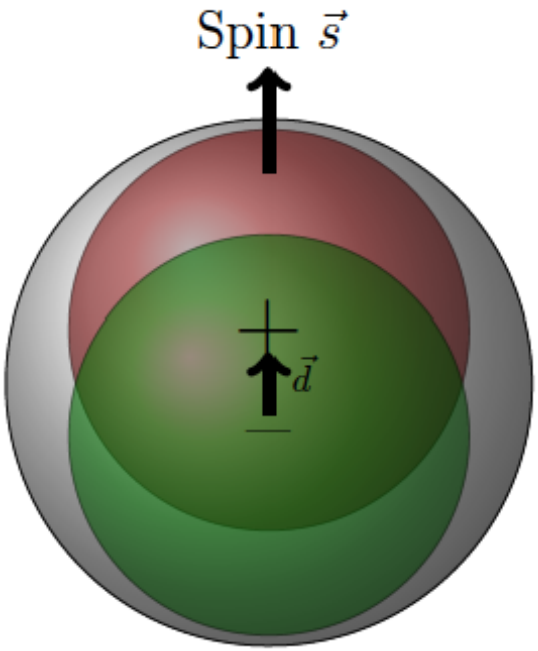
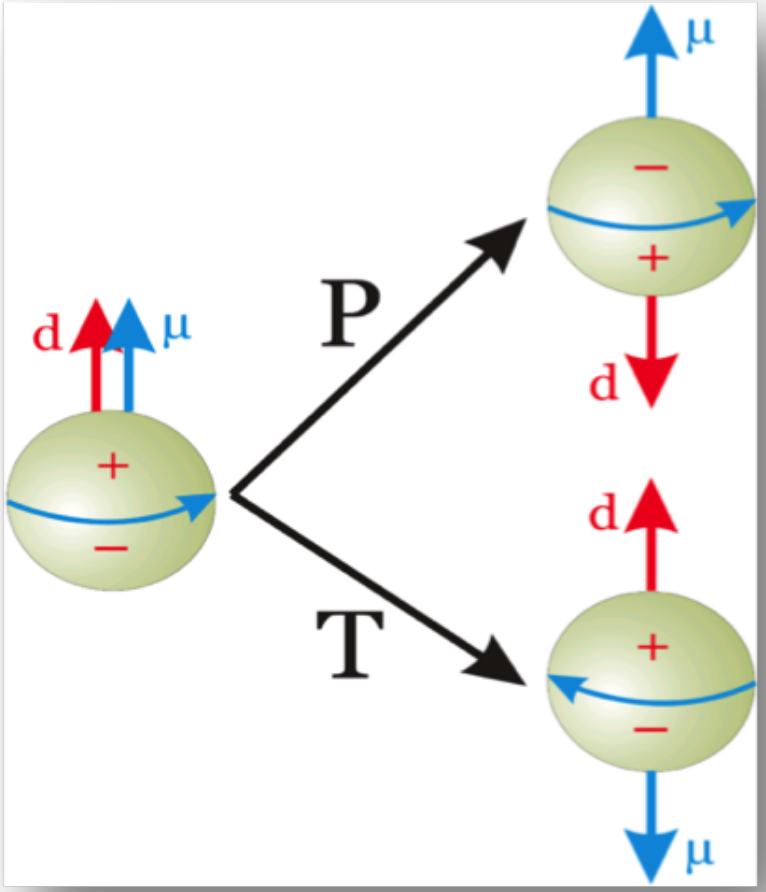


- Permanent separation of + and - charge
- Fundamental property of particles (like magnetic moment, mass, charge)
- Possible via violation of time-reversal (T) and parity (P)
- *Nothing to do with electric dipole moments observed in some molecules (e.g. H_2O molecule)*

T and P violation of EDM



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

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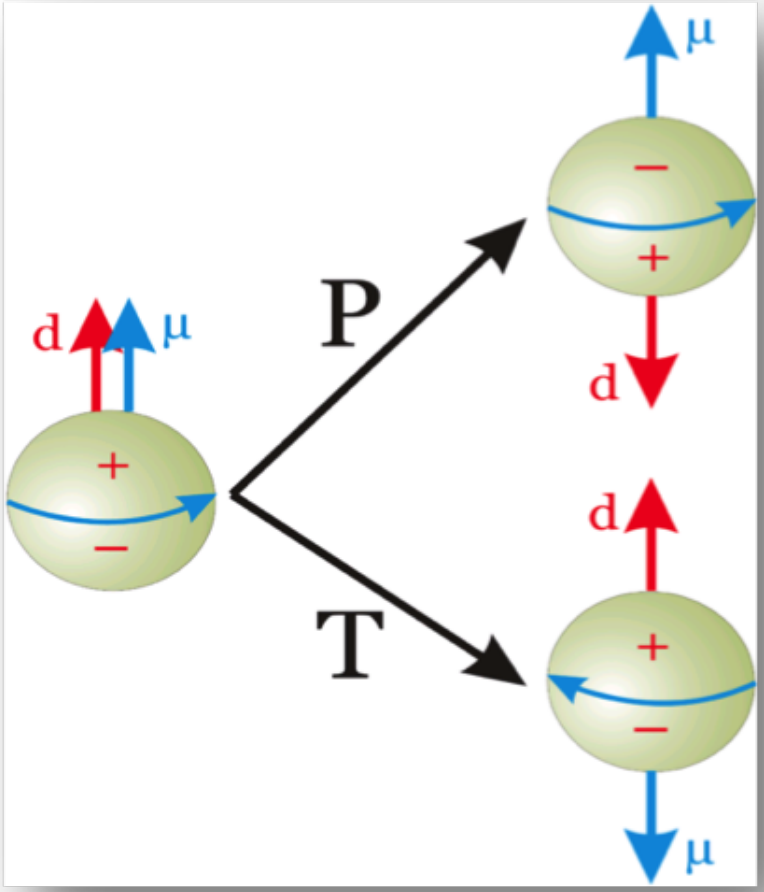

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EDM meas. test violation of P and T symmetries ($\overset{CPT}{=}$CP)

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

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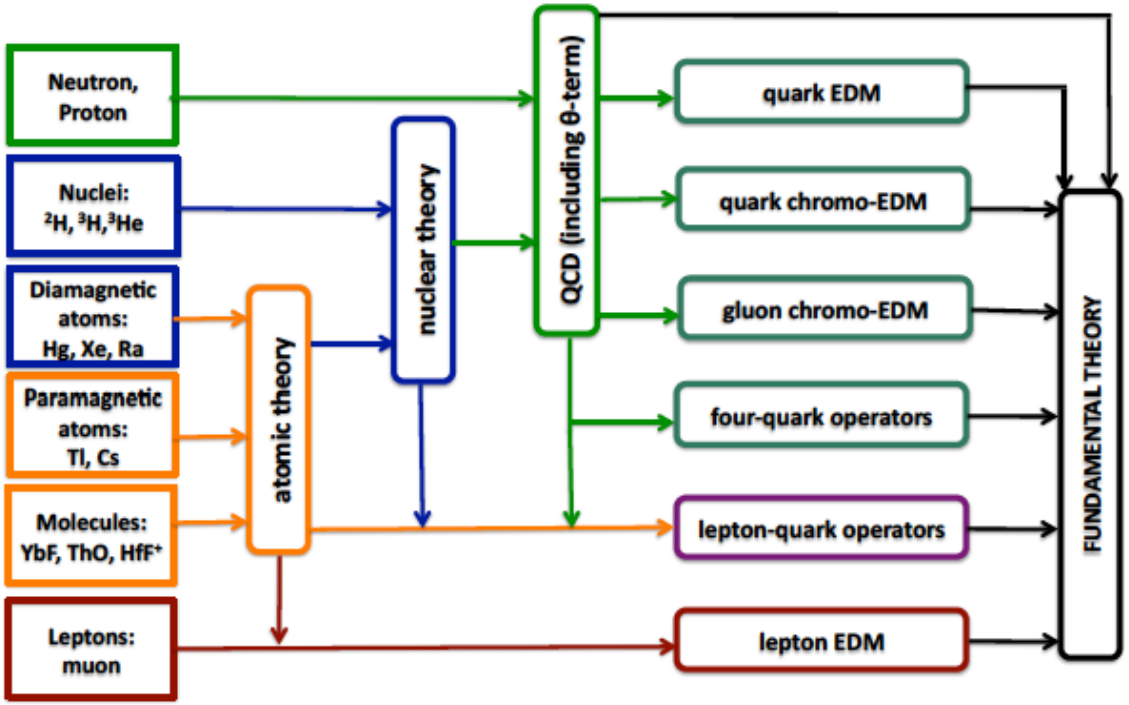
CP violation in SM

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

- ⇒ New CP-V sources beyond SM needed
- Could show up in EDMs of elementary particles

Why charged particles EDMs?

- Static EDM: complementary informations from different systems required
  - Direct measurement and statistical improvement with respect to neutron



J. de Vries

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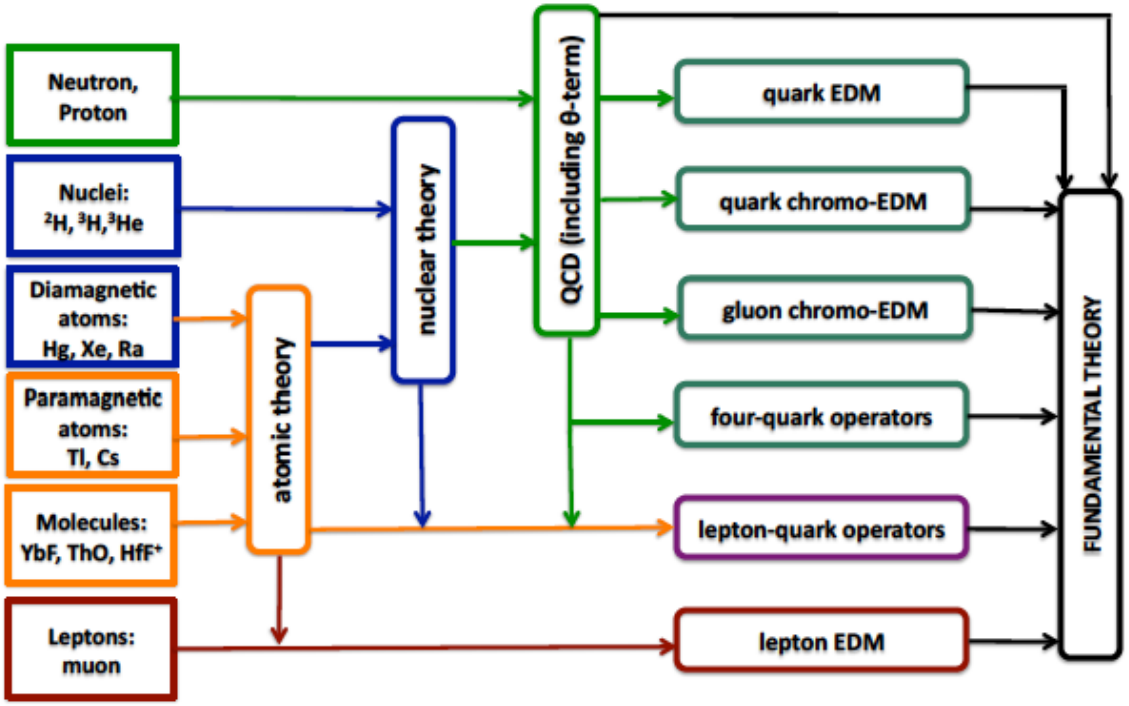

J. de Vries

- Oscillating EDM: axion as a solution to the θ_{QCD} problem
  - Limit on θ_{QCD} comes from n_{EDM}

Experimental method

Spin Precession in a storage ring

Thomas-BMT equation

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = [(\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}) - \vec{\Omega}_{cycl}] \times \vec{s} =$$

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

- 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= $10^{-29} e \cdot cm$)

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Frozen spin

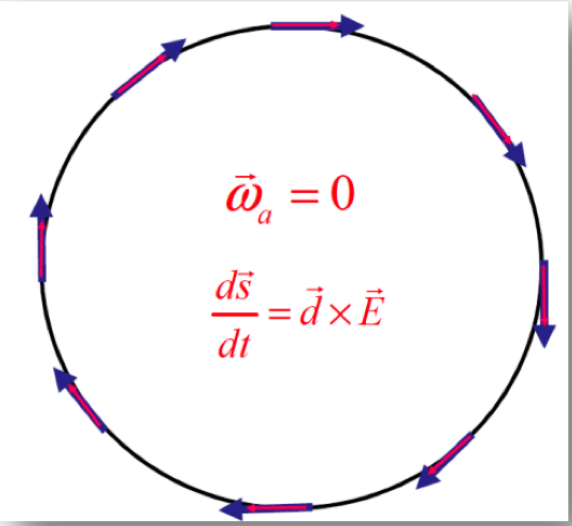
$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[\underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}}_{\Omega_{MDM}-\Omega_{cycl}=0\rightarrow\textbf{frozenspin}} + \frac{\eta}{2}\left(\vec{E} + \vec{v} \times \vec{B}\right)\right] \times \vec{s}$$

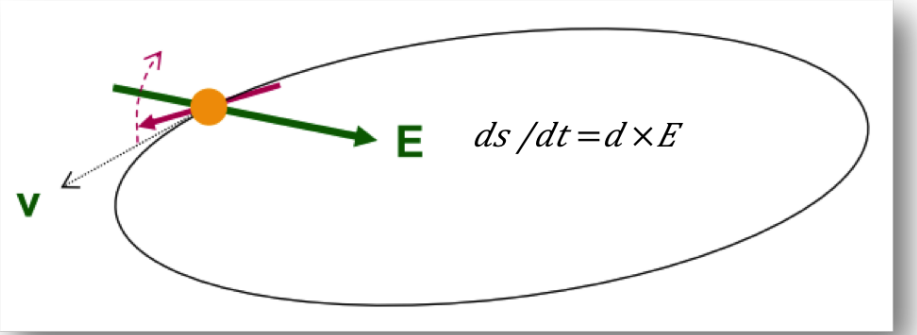
- Achievable with pure electric field for proton (G $>$ 0): $G = \frac{1}{\gamma^2-1}$
- Requires special combination of E, B fields and γ for d, ^3He (G $<$ 0)

Search for static EDM in storage rings

Measurement concept

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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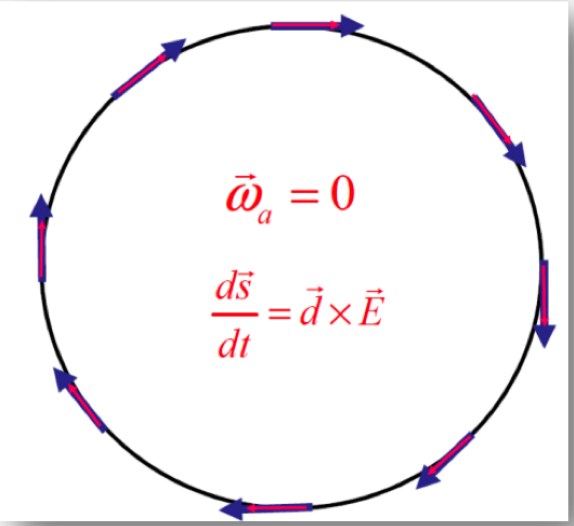

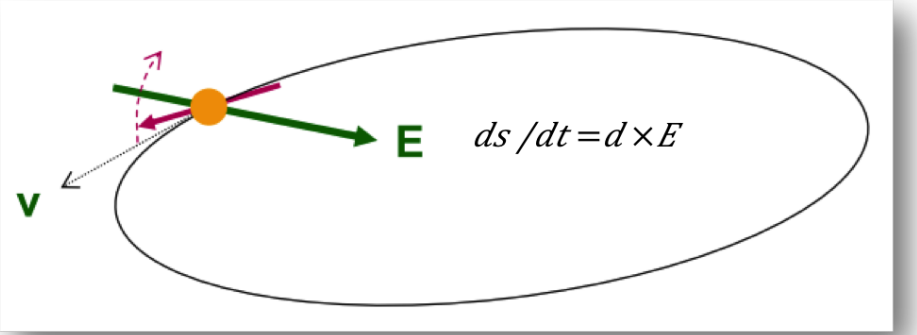

Frozen-spin condition:

- Pure E ring for *p*
- Combined E/B ring for *d* and ^{3}He

Search for oscillating EDM in storage rings

Axions as light dark matter candidates

- Axion interaction with ordinary matter: $\frac{a}{f_0} F_{\mu\nu}\tilde{F}_{\mu\nu}$, $\frac{a}{f_0} G_{\mu\nu}\tilde{G}_{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\bar{\Psi}\gamma^\mu\gamma_5\Psi$
- $\frac{a}{f_0} G_{\mu\nu}\tilde{G}_{\mu\nu} \rightarrow$ coupling to gluons with same structure as QCD-θ term
- Generation of an oscillating EDM

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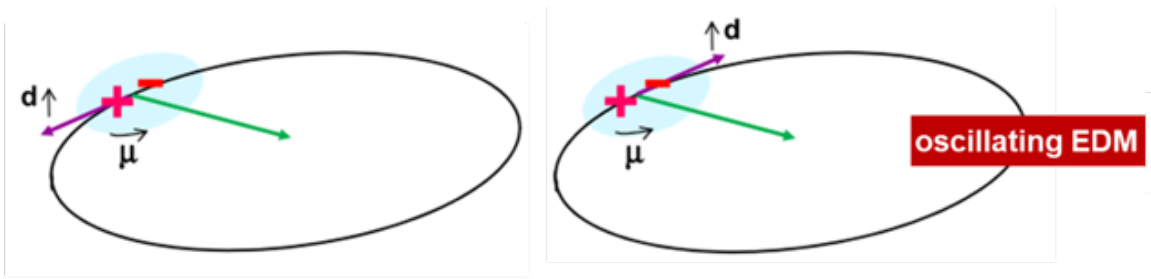

$$\vec{d} = \eta \frac{q\hbar}{2mc}\vec{S}$$

$$\eta = \eta_0 + \eta_1 \sin(\omega_{\text{axion}} t + \varphi_a)$$

$$\omega_{\text{axion}} = \frac{m_a c^2}{\hbar}$$

Combined E/B ring

- Mag. dipole moment (MDM) $\rightarrow$ spin prec. in B field $\rightarrow$ nullifies static EDM effect
- Oscillating EDM resonant condition $\rightarrow$ buildup of out-of-plane spin rotation
- Search of resonance (axion/ALP mass) via change of beam momentum

Requirements

High precision, primarily electric storage ring

- Crucial role of alignment, stability, field homogeneity and shielding from *unwanted* 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 $\sim$ 10 MV/m
- Efficient polarimetry with:
  - large analyzing power: A = 0.6
  - high efficiency detection: eff. = 0.005

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Expected statistical sensitivity in 1 year of data taking:

- $\sigma_{stat} = \frac{\hbar}{\sqrt{Nf}\tau PAE} \Rightarrow \sigma_{stat} = 2.6 \times 10^{-29} e \cdot cm$
- 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 $\cdot$ cm, $E_r = 10$ MV/m
  - Corresponds to $B_r = \frac{dE_r}{\mu} \approx 10^{-17}\,T$

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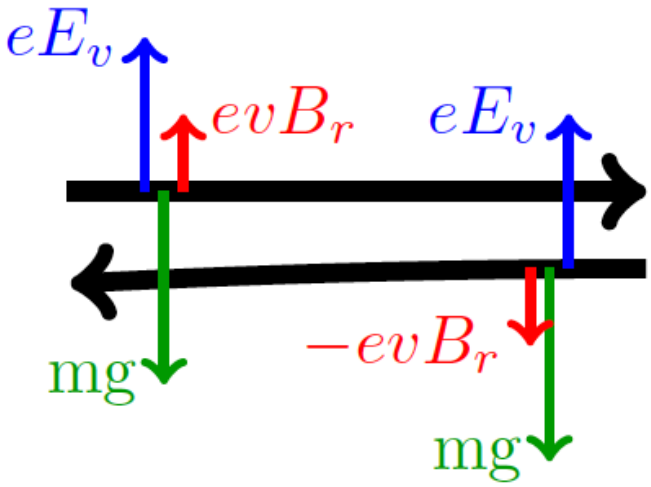
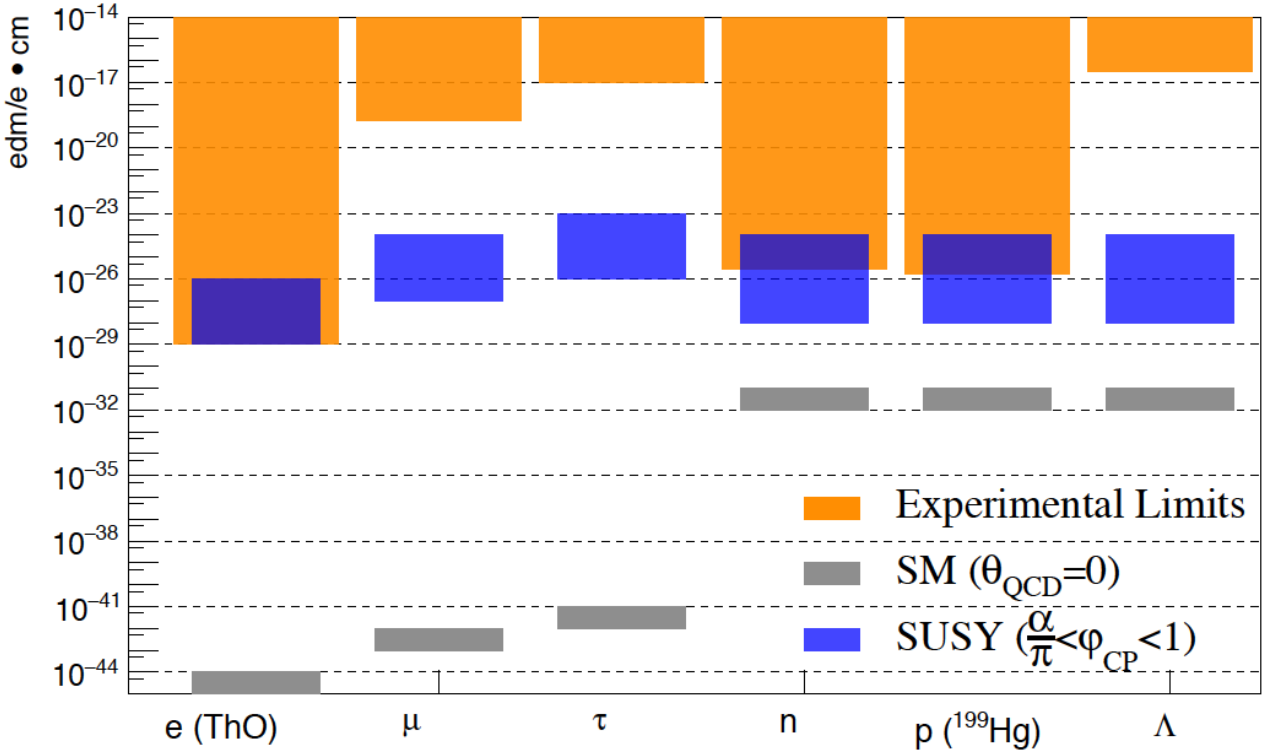
Solution

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

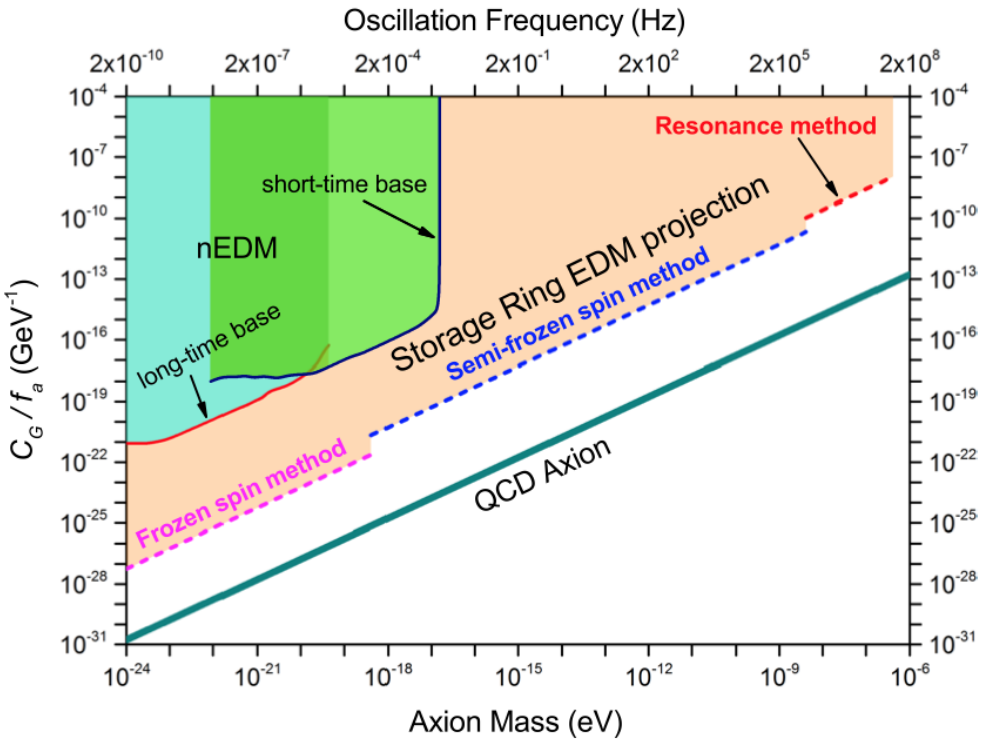


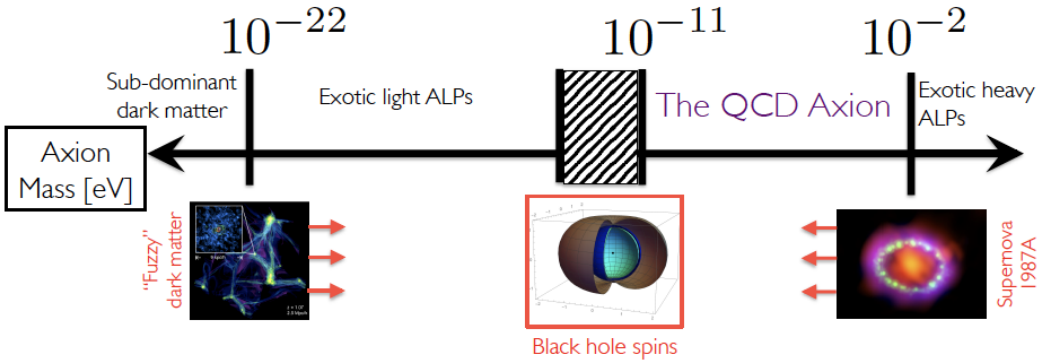
STATIC EDM: current upper limits



- Objective: EDMs of charged hadrons: p, d, $^3\mathrm{He}$
  - Note: current limit on p-EDM: $2.0 \times 10^{-25} e \cdot cm$ (ind. from $d_p^{\downarrow 199Hg}$)
- Final goal: to bring the limit on p to 10^{-29} e · cm

OSCILLATING EDM: axion mass vs gluon coupling





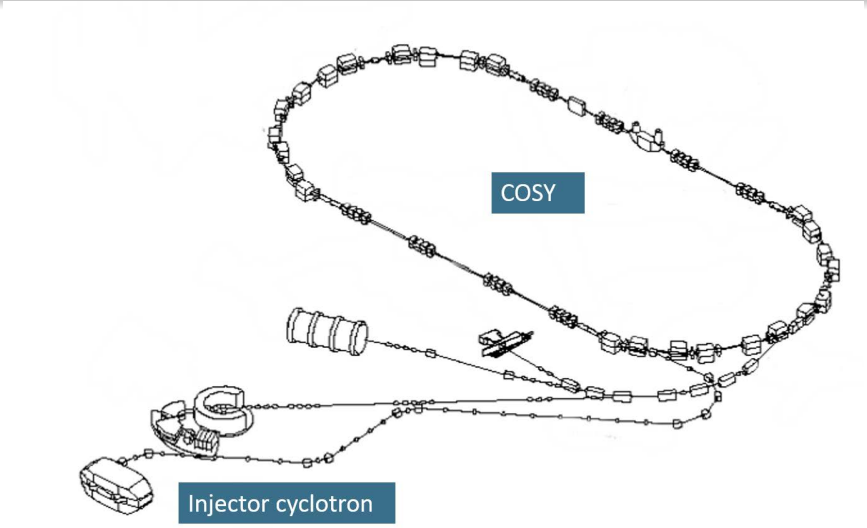
- Experimental limits accessible in one year per single frequency measurement.

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



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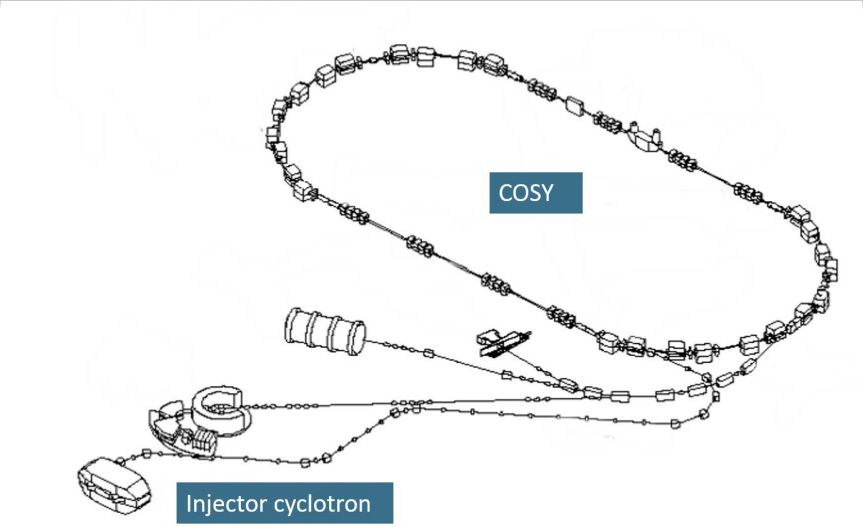
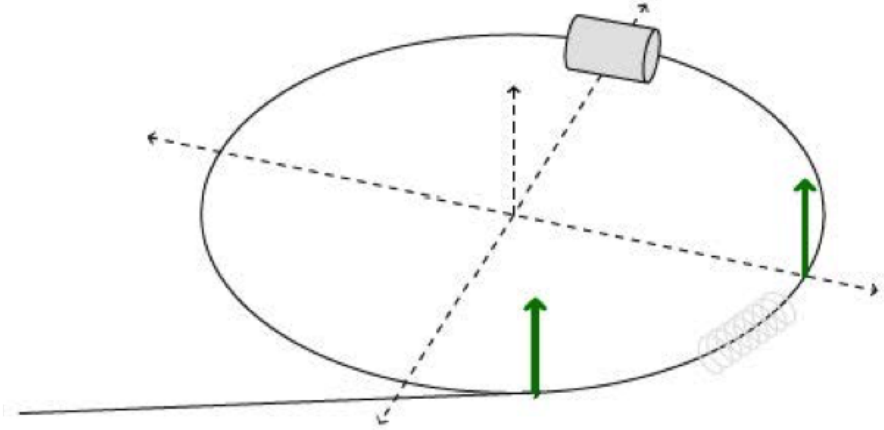


Formerly used as spin-physics machine for hadr. physics:

- 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



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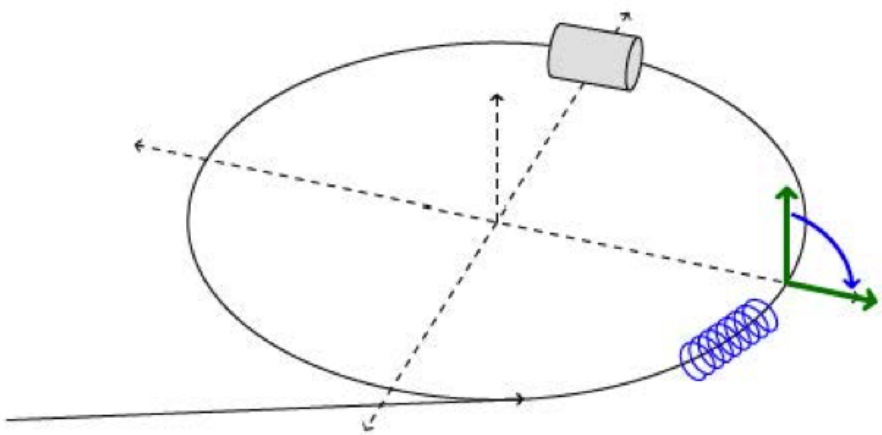
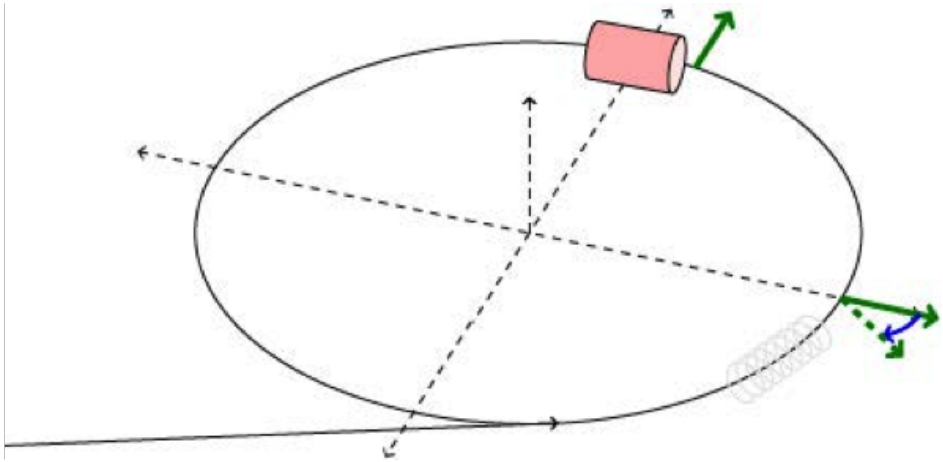


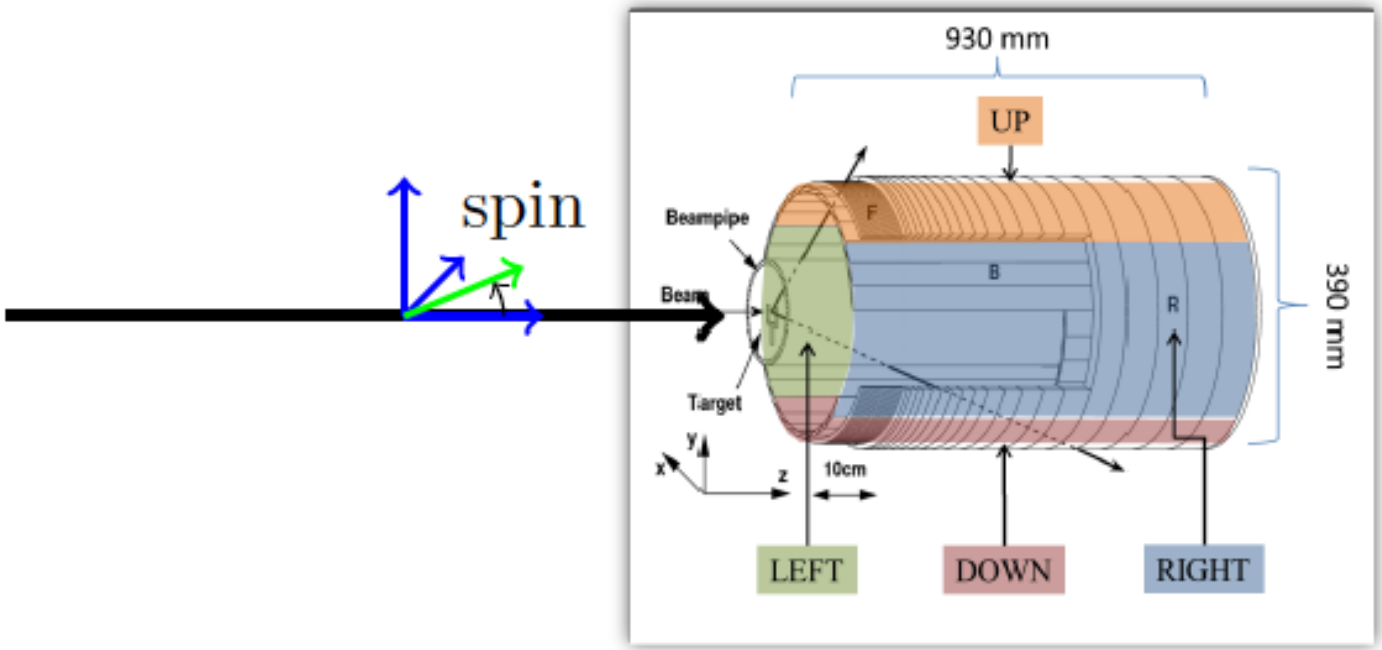
Experiment preparation

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



Time-stamp system

Asymmetry: $\epsilon = \frac{N_{up} - N_{down}}{N_{up} + N_{down}} = p_z A_y \sin\left(2\pi \cdot \nu_s \cdot n_{turns}\right)$

Challenge

- Spin precession frequency: 126 kHz
- ν_s = 0.16 $\rightarrow$ 6 turns/precession
- event rate: 5000 s^{-1} $\rightarrow$ 1 hit / 25 precessions $\rightarrow$ no direct fit of rates

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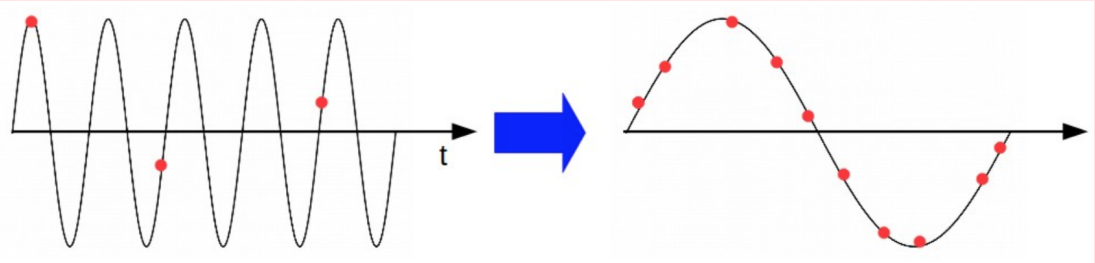
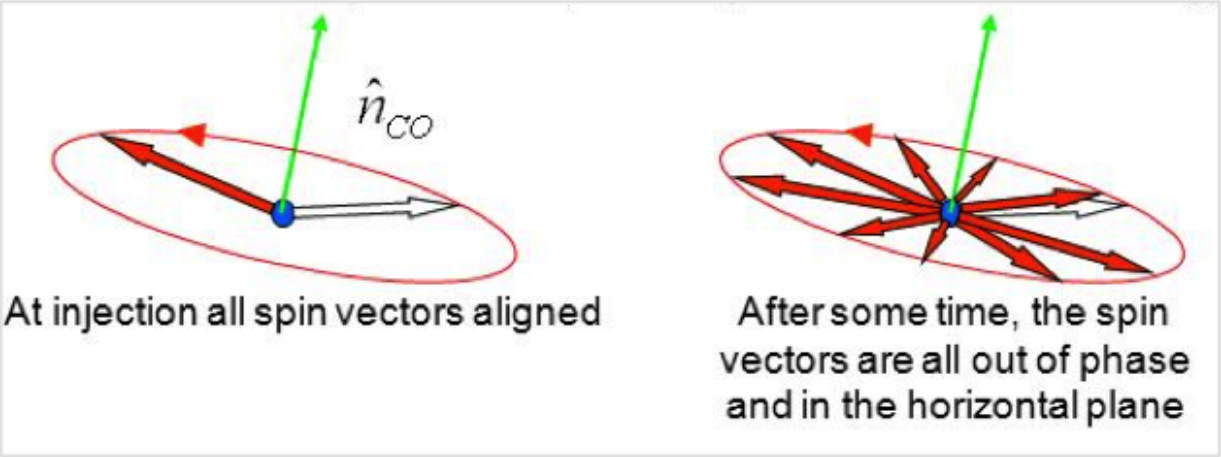
Solution: map many event to one cycle

- Counting turn number n $\rightarrow$ phase advance $\phi_s = 2\pi\nu_s n$
- For intervals of $\Delta n = 10^6$ turns: $\phi_s \rightarrow \phi_s$ mod 2π

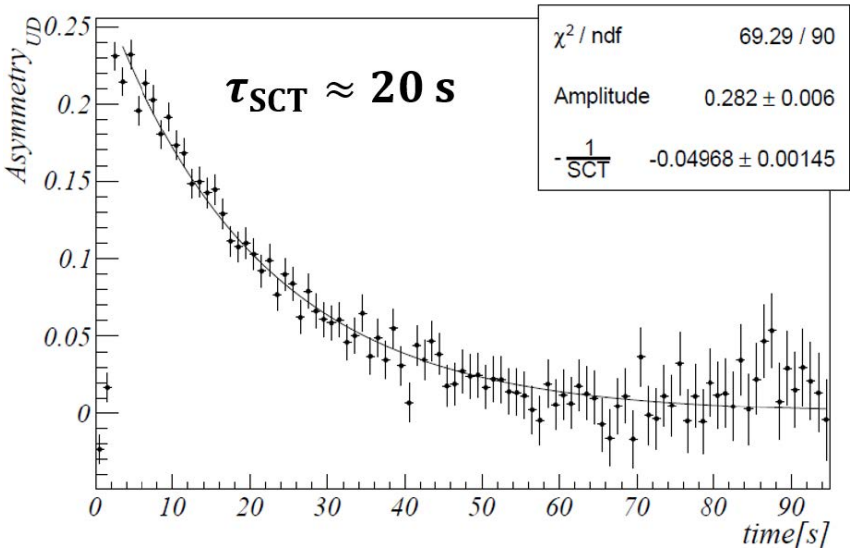


Optimization of spin-coherence time



2012: First result

- Bunched beam to increase SCT



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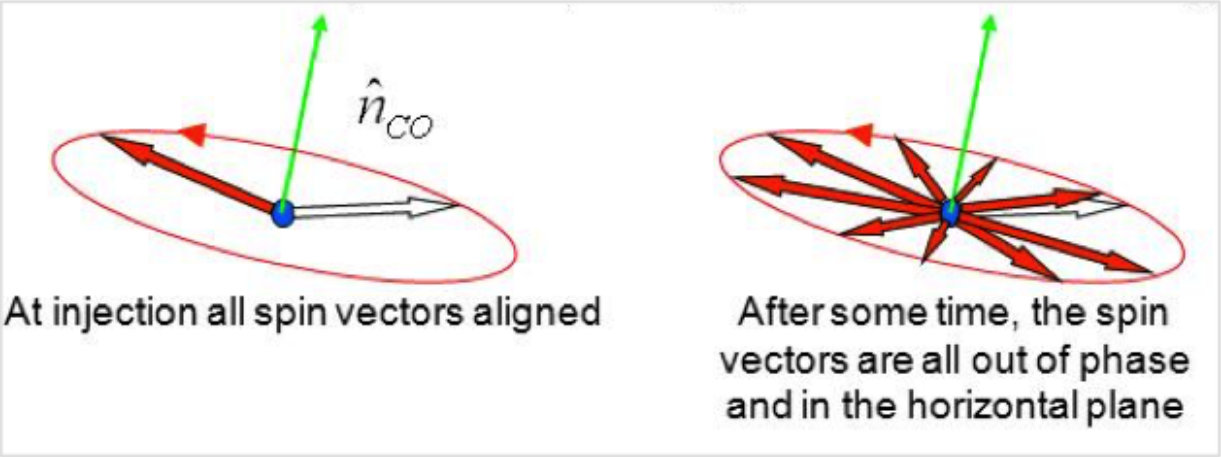

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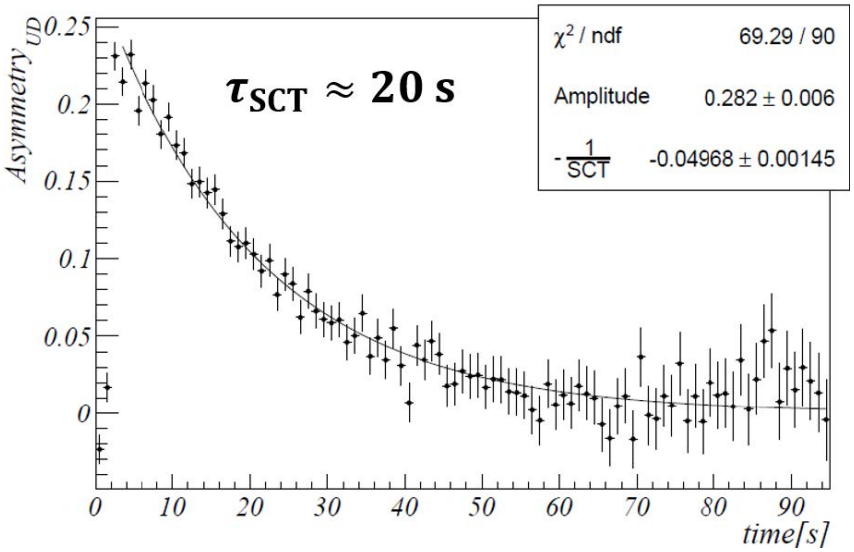
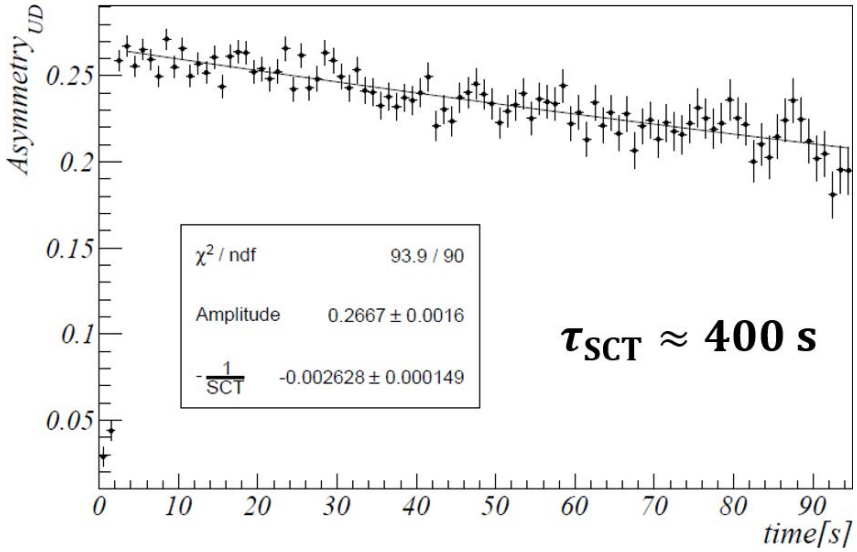
2013: improvement

- 6-poles correct higher order effects.





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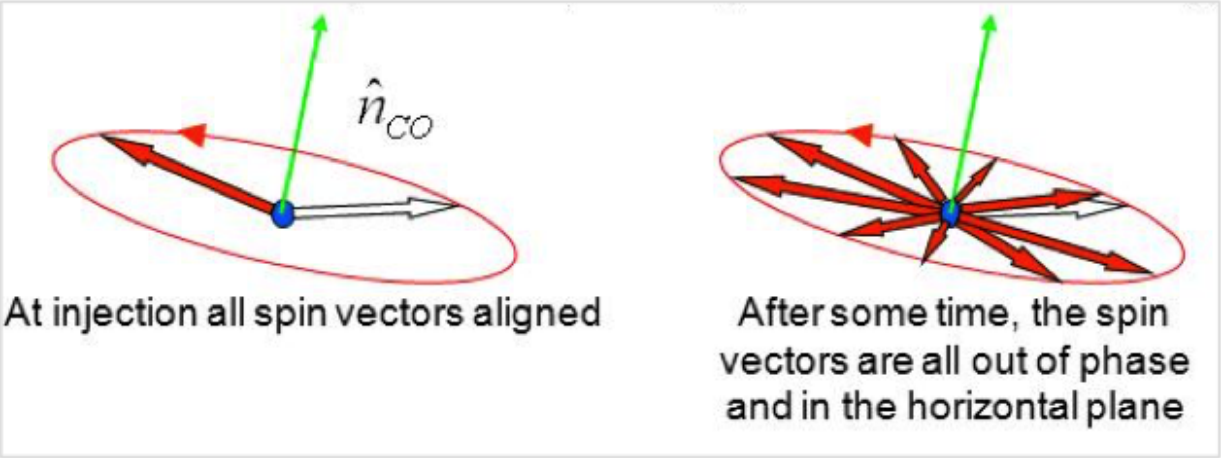

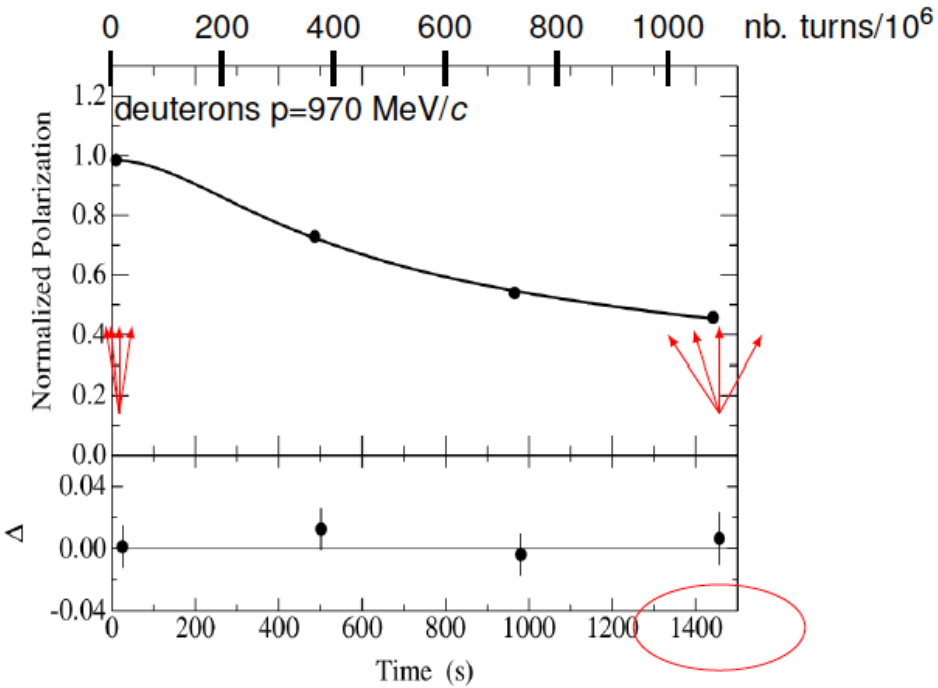

I major achievement
[Phys. Rev. Lett. 117 (2016) 054801]

- τ_{SCT} = (782 ± 117)s
- Previously: τ_{SCT}(VEPP) ≈ 0.5 s (≈ 10^7 spin revolutions)
- SCT of crucial importance, since $\sigma_{STAT} \propto \frac{1}{\tau_{SCT}}$

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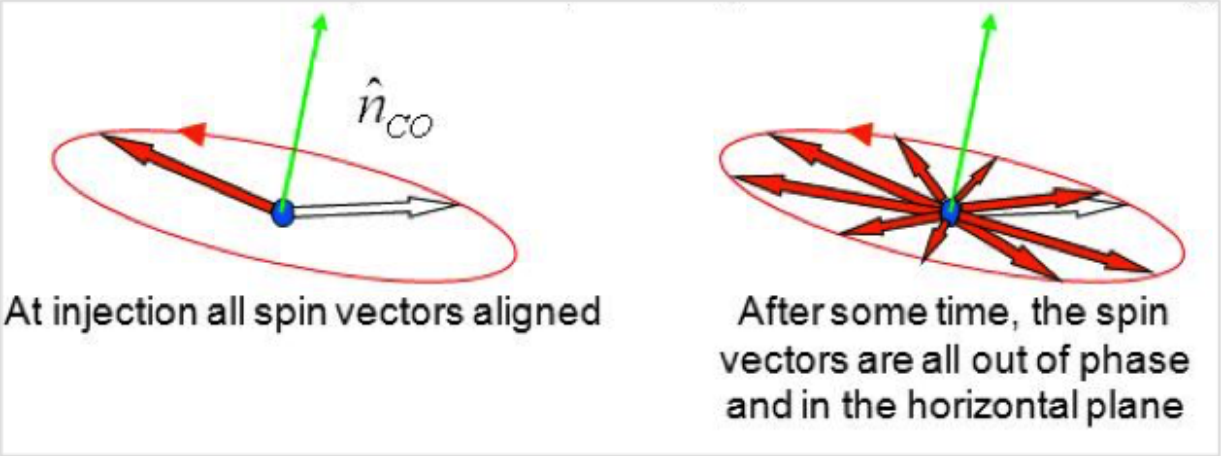

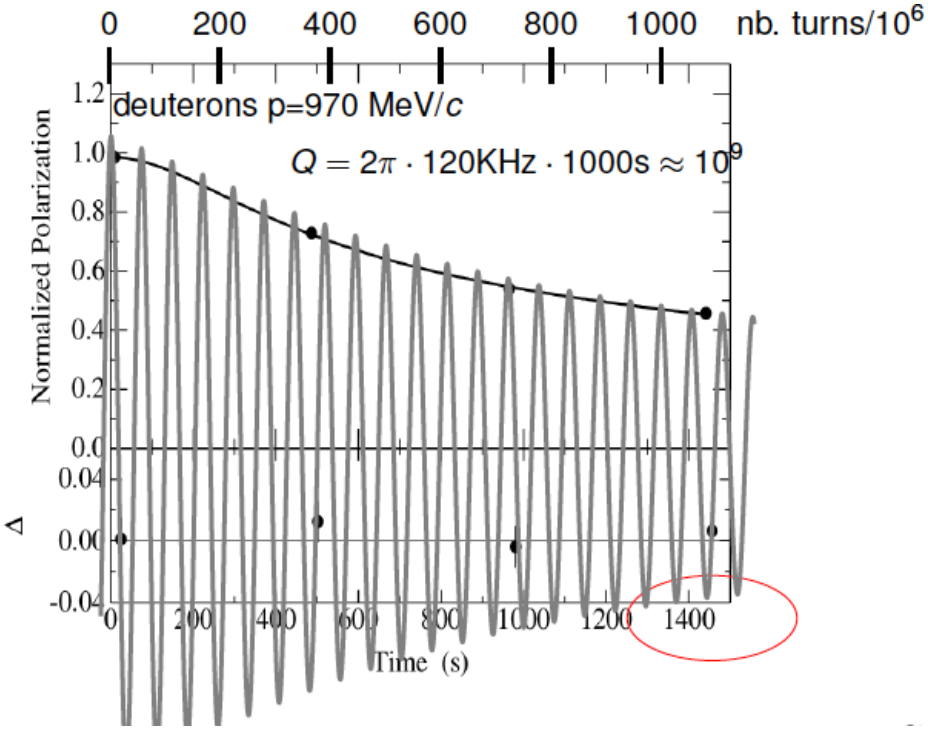

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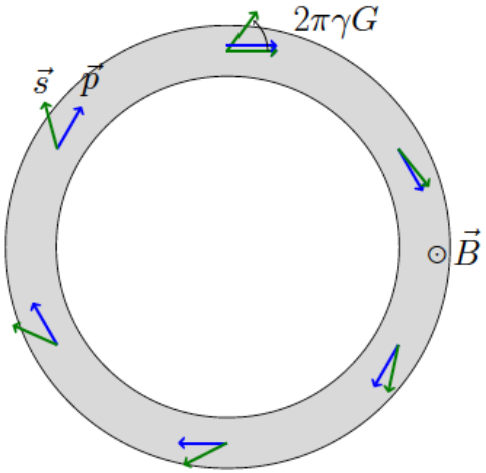
- SCT of crucial importance, since $\sigma_{STAT} \propto \frac{1}{\tau_{SCT}}$

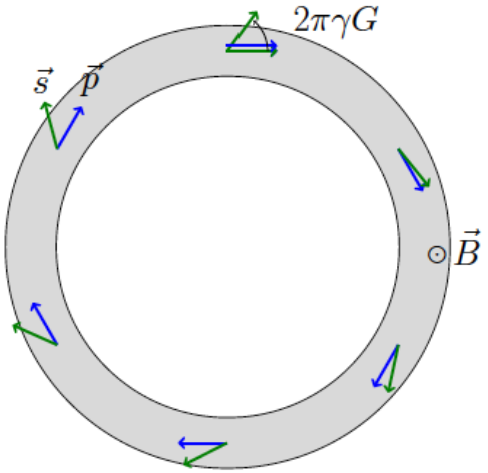
Precise determination of the spin-tune

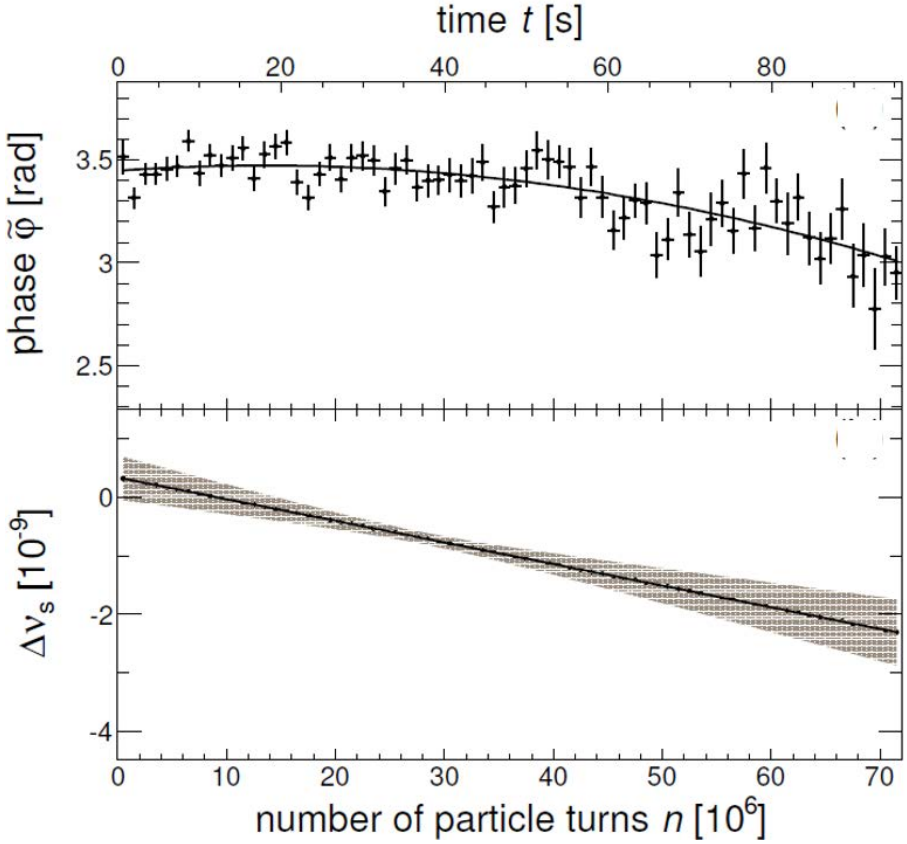


Spin-tune ν_s

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

Precise determination of the spin-tune





Spin-tune ν_s

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

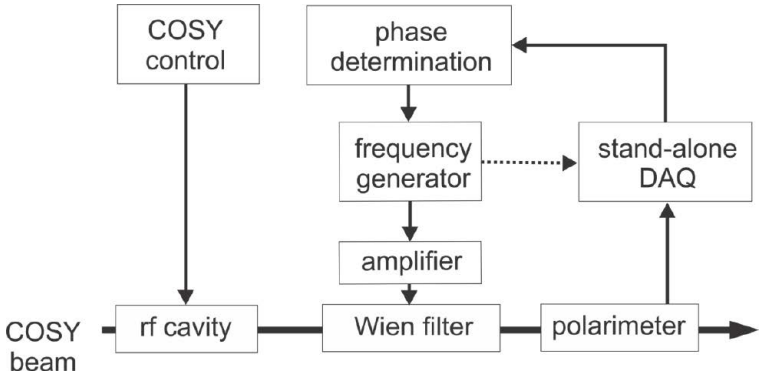
II major achievement *[Phys. Rev. Lett. 115 (2015) 094801]*

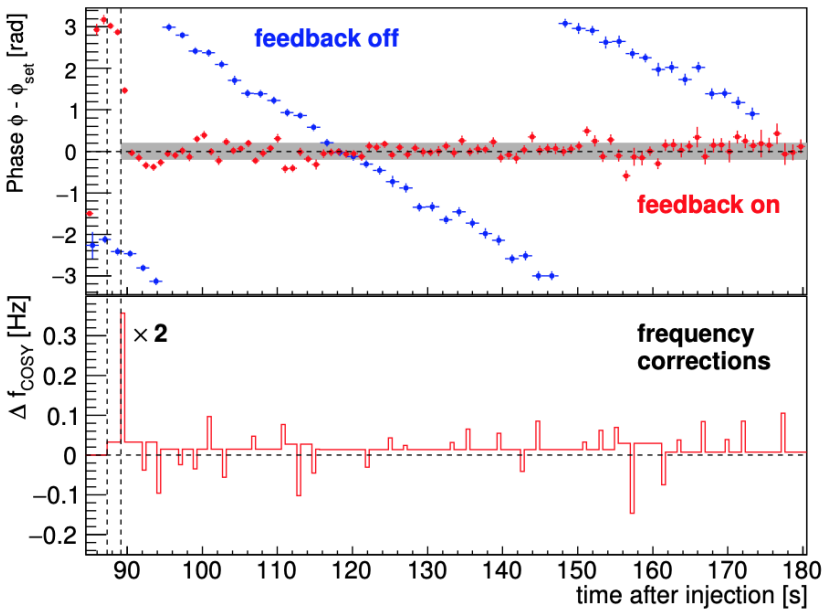
- Interpolated spin tune in 100 s:
- $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$ $(\Delta\nu_s/\nu_s \approx 10^{-10})$
- Angle precision: $2\pi \times 10^{-10}$ = 0.6 nrad
- Previous best: 3×10^{-8} per year (g-2 experiment)
- $\rightarrow$ new tool to study systematic effects in storage rings

Phase locking spin precession in machine to device RF

Spin-feedback system maintains:

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





III major achievement *[Phys. Rev. Lett. 119 (2017) 014801]*:

Error of phase-lock σ_ϕ = 0.21 rad

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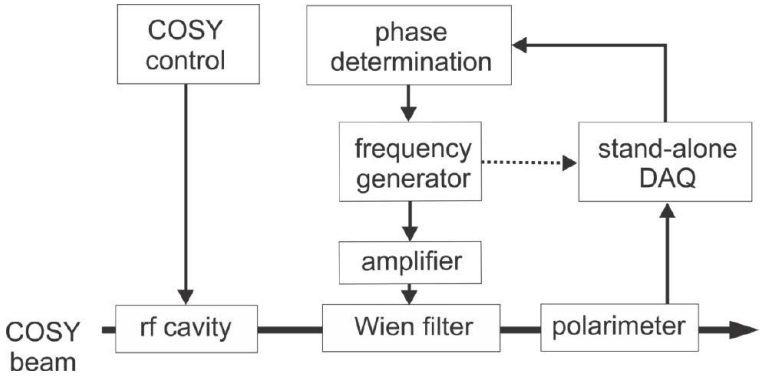
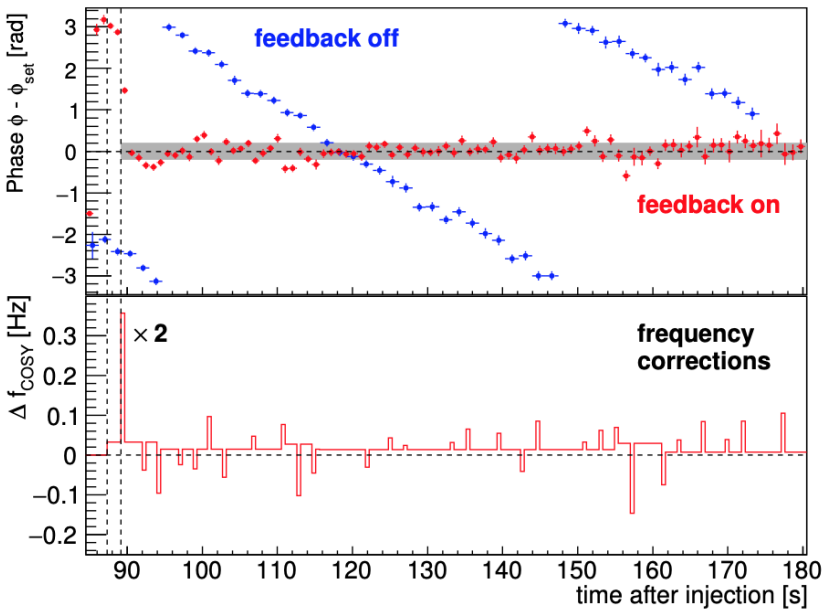




III major achievement *[Phys. Rev. Lett. 119 (2017) 014801]*:

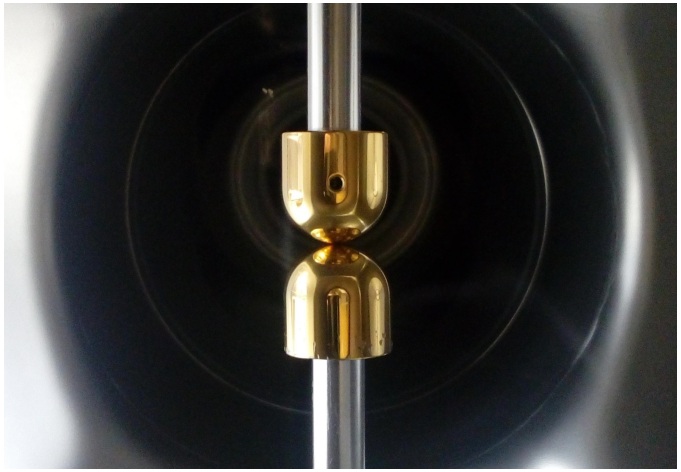
Error of phase-lock σ_ϕ = 0.21 rad

At COSY freezing of spin precession not possible
$\rightarrow$ phase-locking required to achieve precision for EDM

Other technological developments

E/B deflector development using small-scale setup

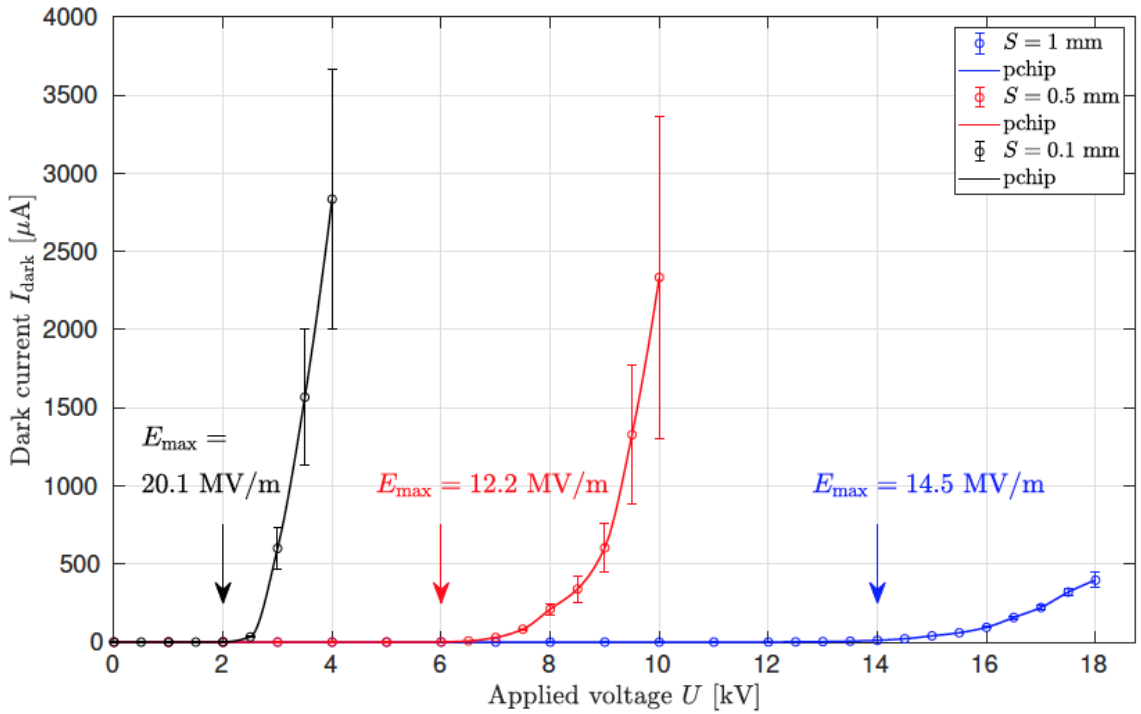
- Polished stainless steel
  - 240 MV/m at 0.05 mm with half-sphere facing flat surface
  - 17 MV/m with 1 kV at 1 mm with two small half-spheres
- Polished aluminum
  - 30 MV/m at 0.1 mm using two small half-spheres
- TiN coating
  - Smaller breakdown voltage
  - Zero dark current



Dark current measurements

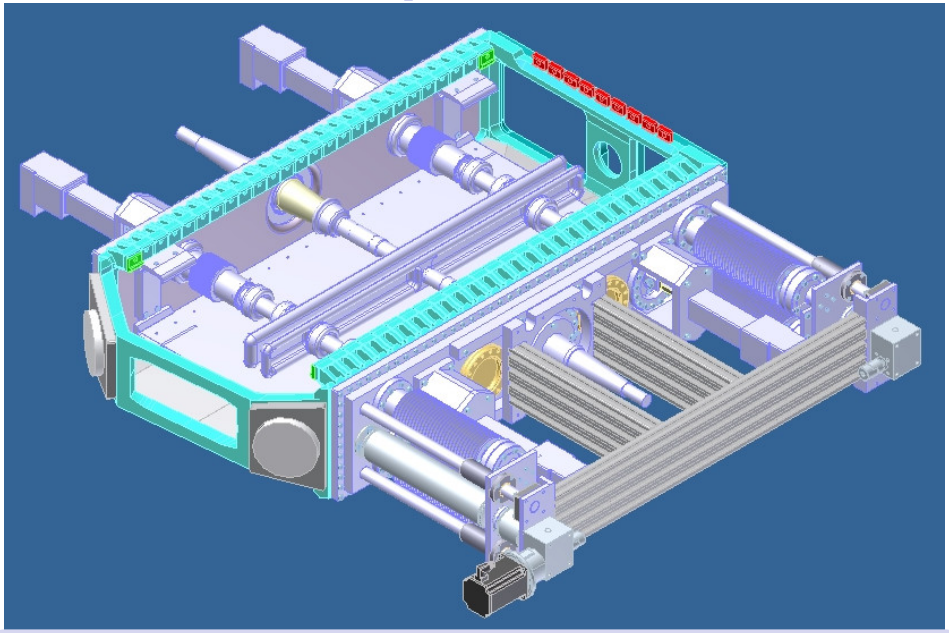
Dark current stainless-steel half-sphere electr. (R=10 mm)

- Distances S = 1, 0.5 and 0.1 mm where:
  $E_{max} = \frac{U}{S} \cdot F$, where $F = \frac{1}{4}\left[1 + \frac{S}{R} + \sqrt{\left(1 + \frac{S}{R}\right)^2 + 8}\right]$



Promising → tests with real size deflector elements required

E/B deflector development using real-scale setup



Equipment

- Dipole magnet B_{max} = 1.6 T
- Mass = 64 t
- Gap height = 200 mm
- Protection foil between chamber wall and detector

Parameters

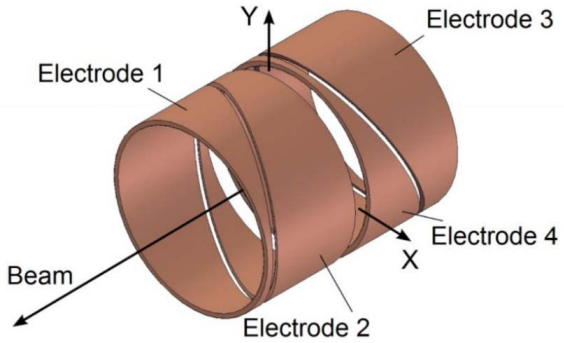
- Electr. length = 1020 mm
- Electr. height = 90 mm
- Electr. spacing = 20 to 80 mm
- Max potential = $\pm$ 200 kV
- Material: Al coated with TiN

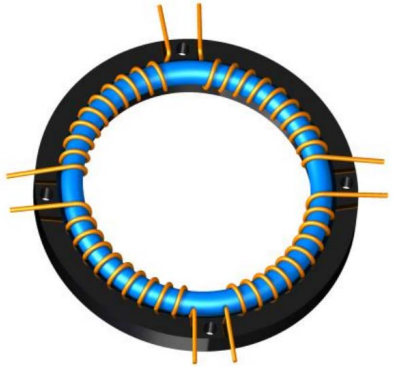
- First results expected soon

Beam position monitors for srEDM experiments

Development of compact BPM based on Rogowski coil

- Main adv.: short install. length ($\approx$ 1 cm in beam direction)





Conventional BPM

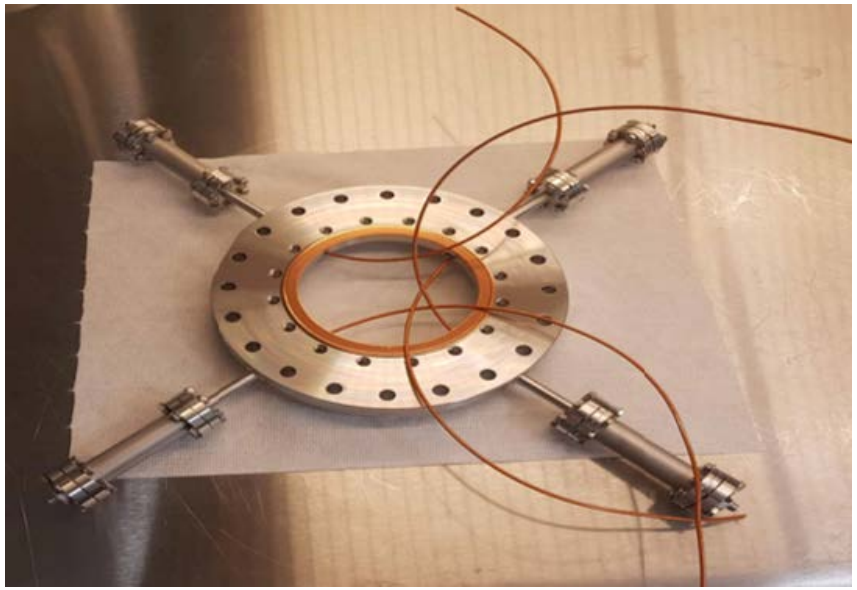
- Easy to manifacture
- Length = 20 cm
- Resolution $\approx$ 10 μm

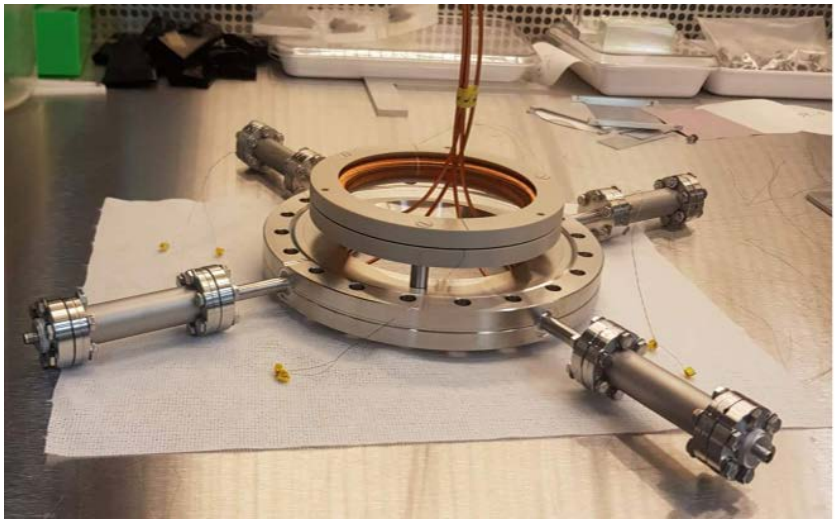
Rogowski BPM (warm)

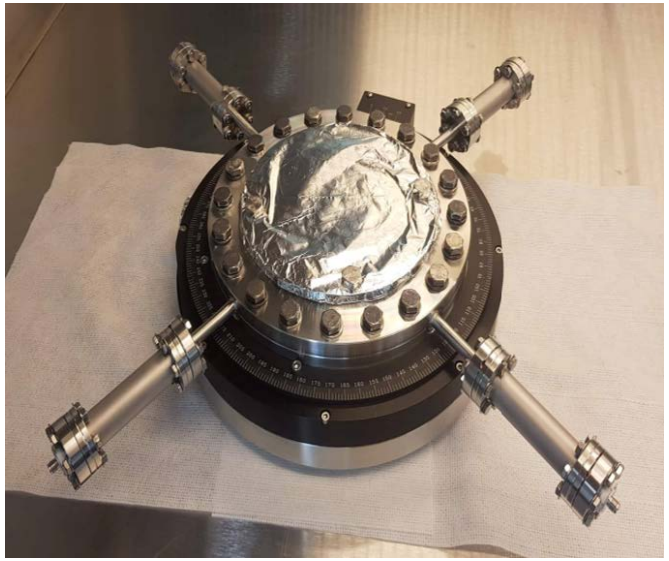
- Excellent RF-signal response
- Length = 1 cm
- Resolution $\approx$ 1.25 μm

- 2 coils installed at entrance and exit of RF Wien filter

Assembly stages of one Rogowski-coil BPM







High-precision beam polarimeter with internal C target

Based on LYSO scintillator readout by SiPM

- Saint-Gobain Ceramics & Plastics
- Compared to NaI:
  - high density (7.1 vs 3.67 g/cm^3),
  - fast decay time (45 vs 250 ns).

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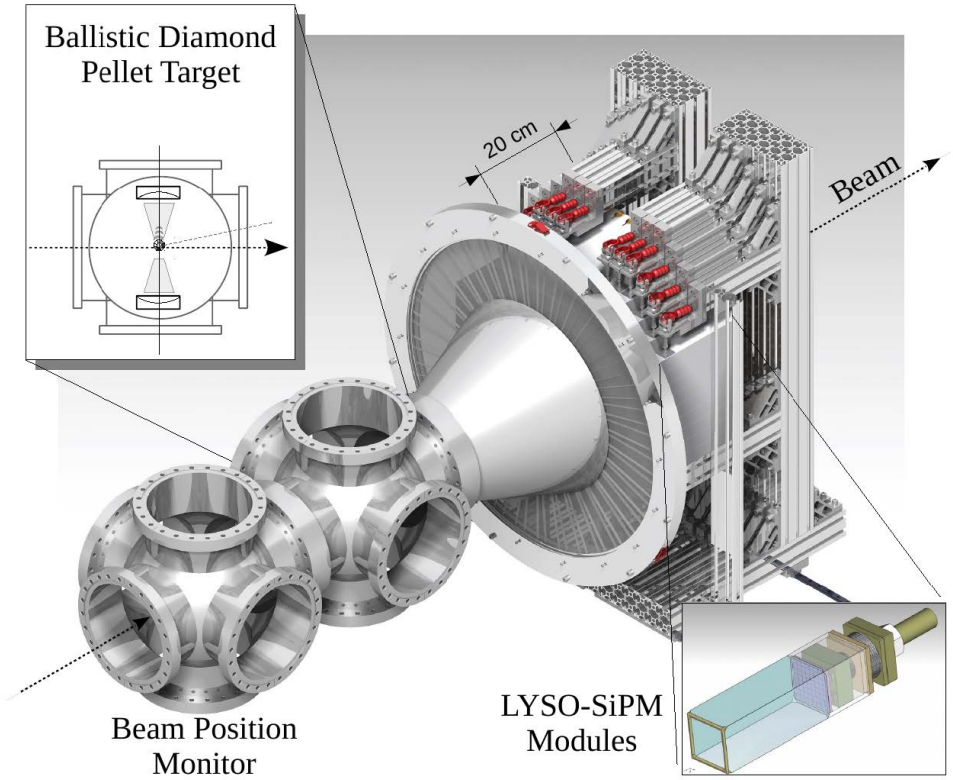
  - high density (7.1 vs 3.67 g/cm^3),
  - fast decay time (45 vs 250 ns).

After runs with external beam:

- System installed in Spring 2020.
- Under study: Ballistic diamond pellet target for homogeneous beam sampling.



Towards a storage ring EDM measurement

Strategy: staged approach to a storage ring for precision physics

On the basis of the preparedness of the required technological developments

Stage 1

precursor experiment

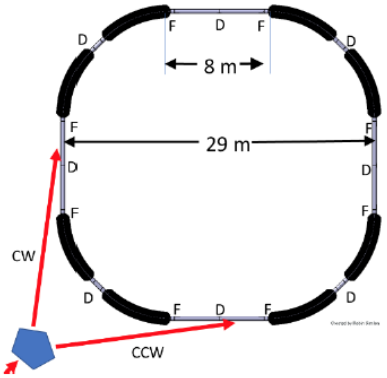
at COSY (FZ Jülich)

- magnetic storage ring

now

Stage 2

prototype ring

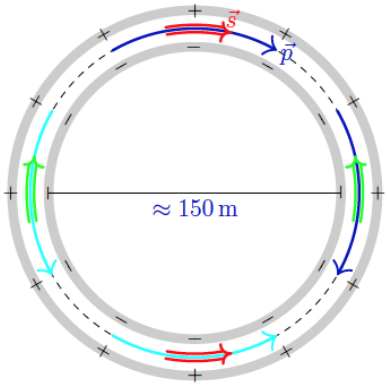


- electrostatic storage ring
- simultaneous ↻ and ↺ beams

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}

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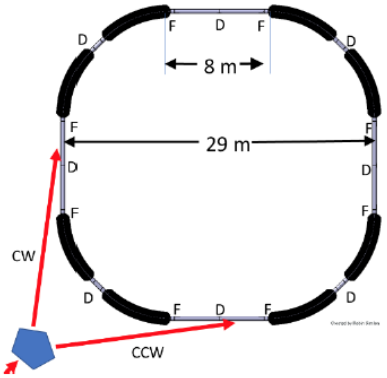

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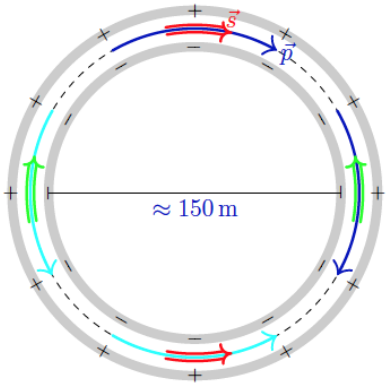

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Planned Design Study application: Prototype ring for charged particle EDM searches

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

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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

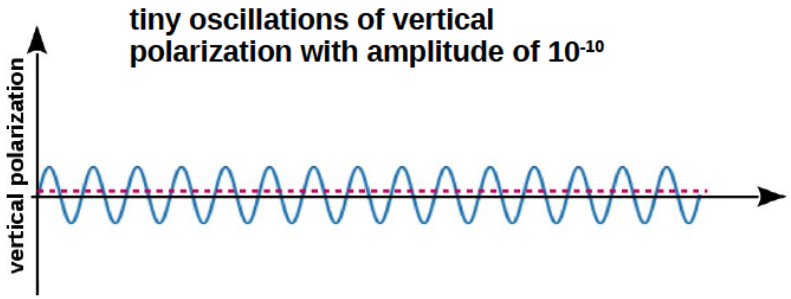
- Pure magnetic ring $\rightarrow$ motional electric field: $\vec{v} \times \vec{B}$
- $\Rightarrow$ access to EDM

RF-Wien filter

- Exploitation of motional electric field in particle rest frame: $E^* = v \times B$

Magnetic ring

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



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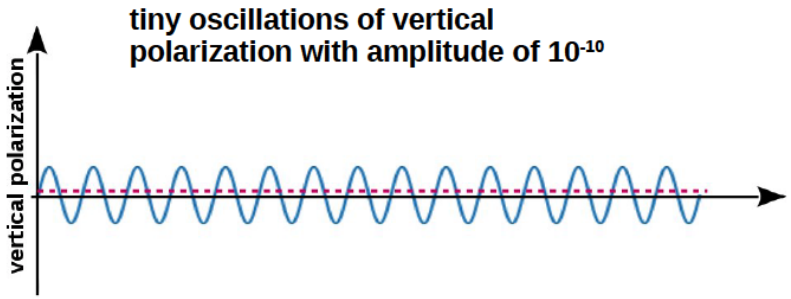
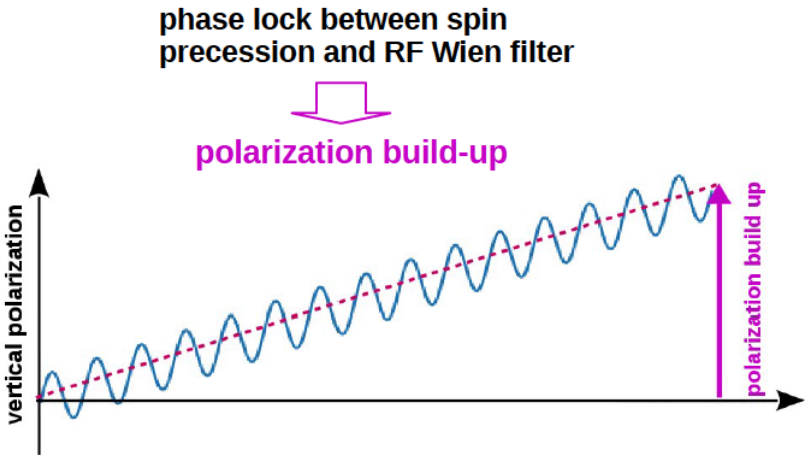


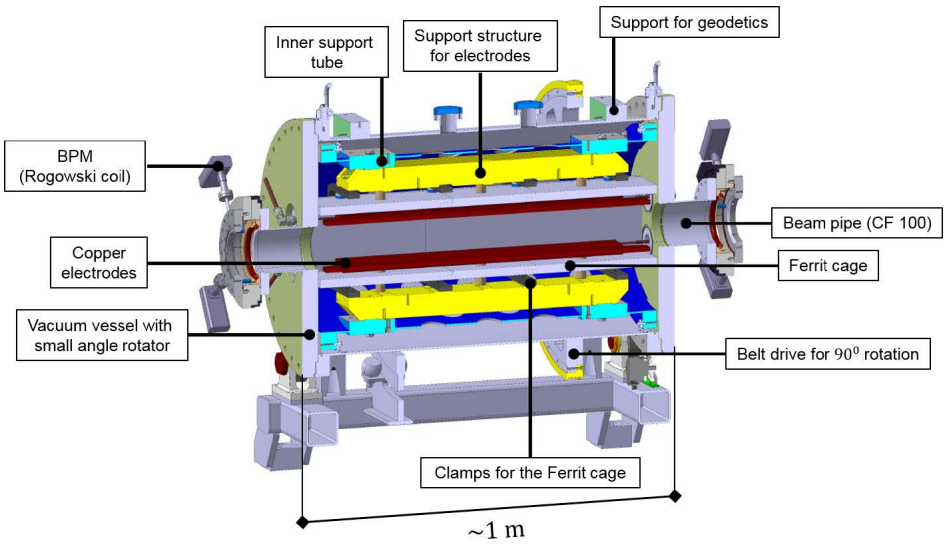
RF-Wien filter

- 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



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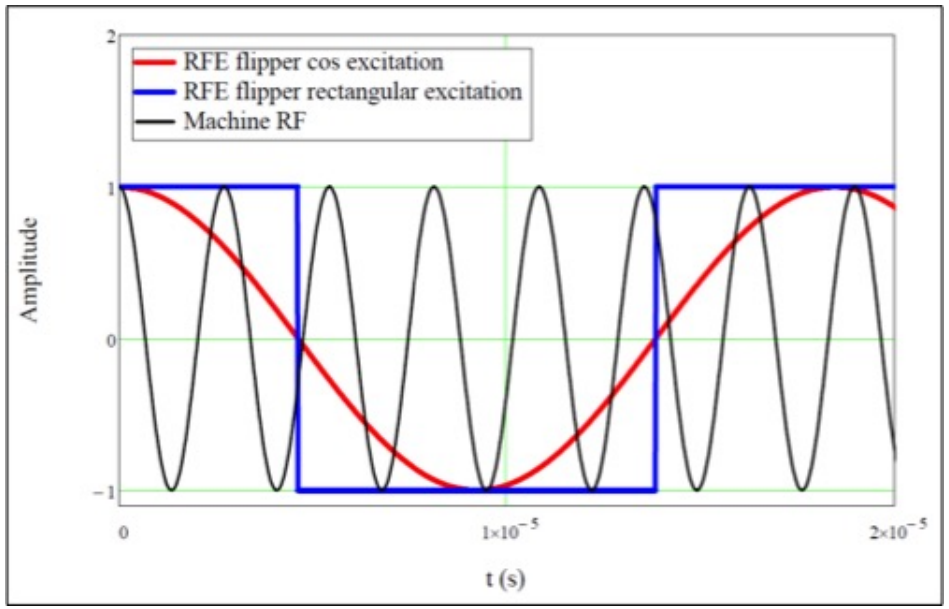
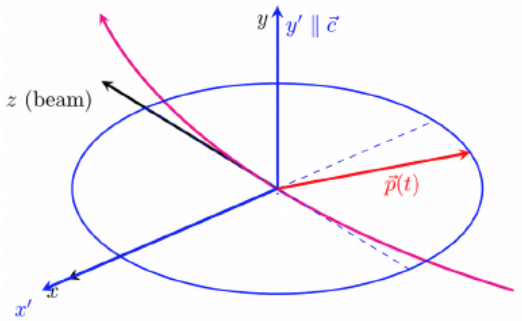
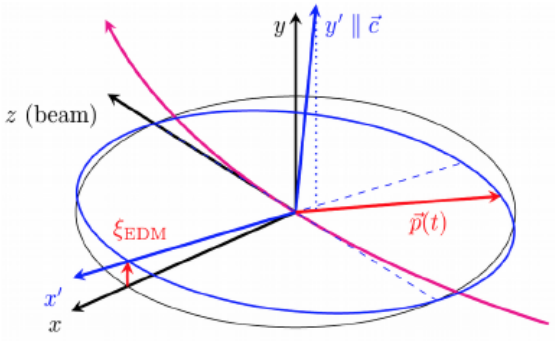
- RF-Wien filter operation:



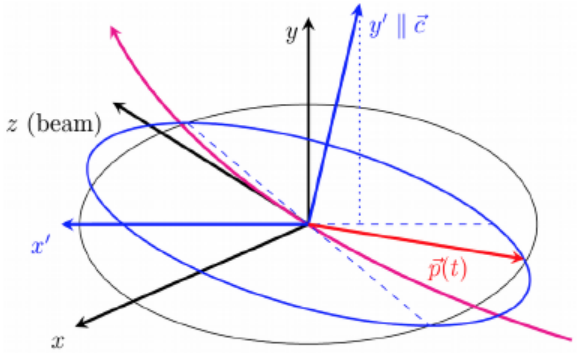
Effect of EDM on stable spin-axis



EDM absence



EDM effect

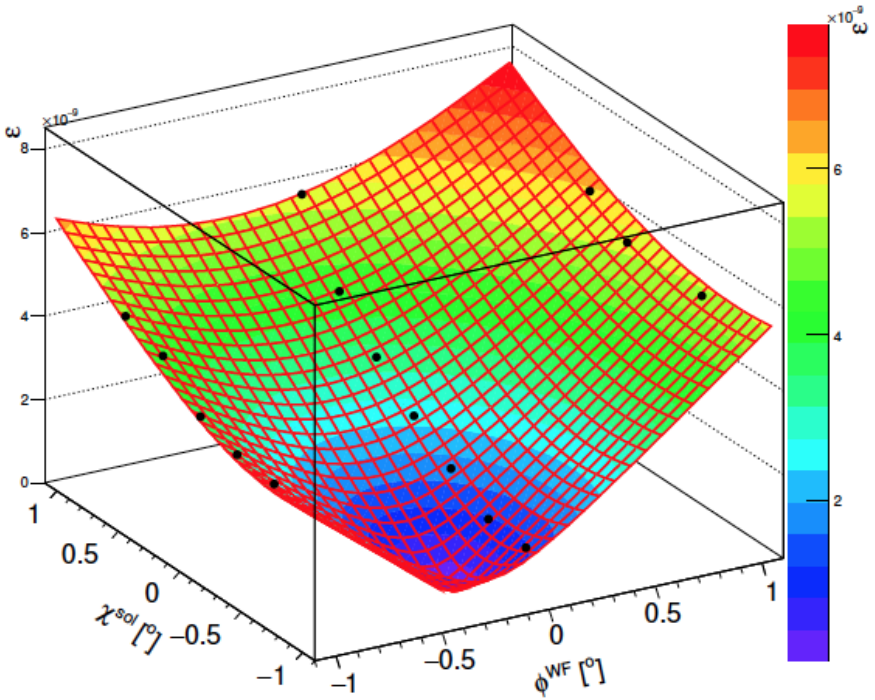


Magnetic misalignment

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 $p_y(t)$

Preliminary results from run in Dec. 18 + Feb./Apr. 21



(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
- Results foreseen by end of 2021

Next steps

Stage 2: prototype EDM storage ring

- Build demonstrator for charged particle EDM
  - Key-performance enabler for the final ring
- Project prepared by CPEDM working group (CERN+JEDI)
  - P.B.C. process (CERN) & European Strategy for Particle Physics Update
- Possible host sites: COSY or CERN
- S.R. to Search for EDMs of Charg. Part. - Feas. Study (arXiv:1912.07881)

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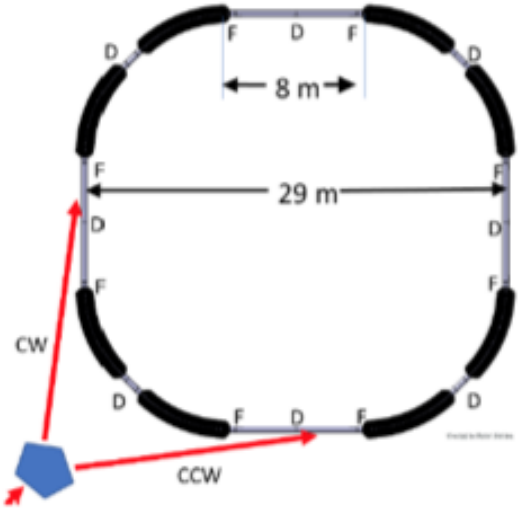
100 m circumference

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



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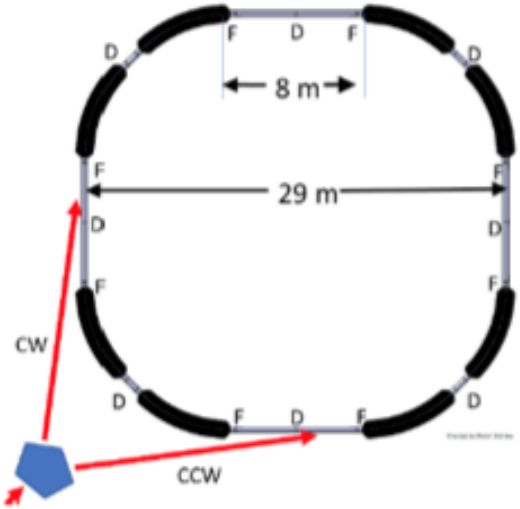
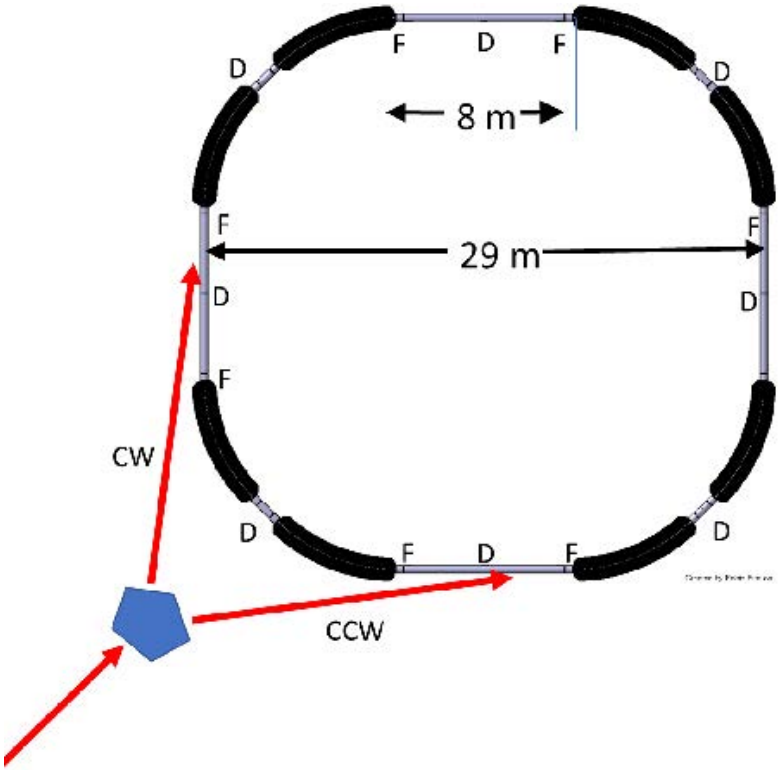


Challenges

- All electric & E-B combined deflection
- Storage and spin-coher. time in elec. machine
- CW-CCW operation
- Orbit control
- Polarimetry
- Magnetic moment effects
- Stochastic cooling

Development: bending elements



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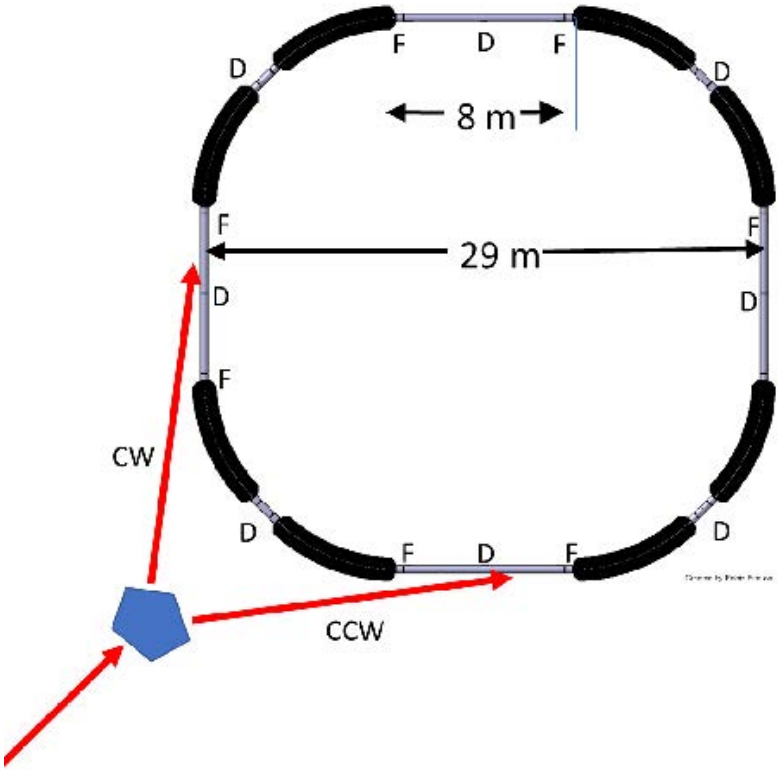
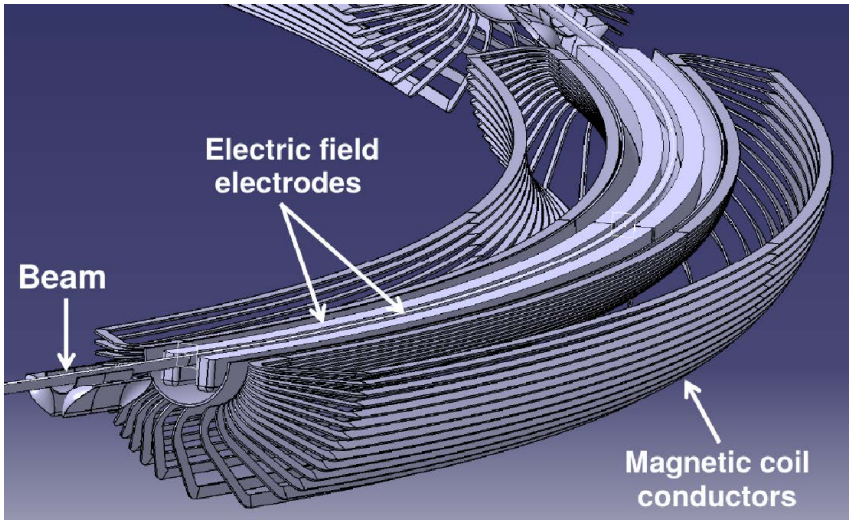
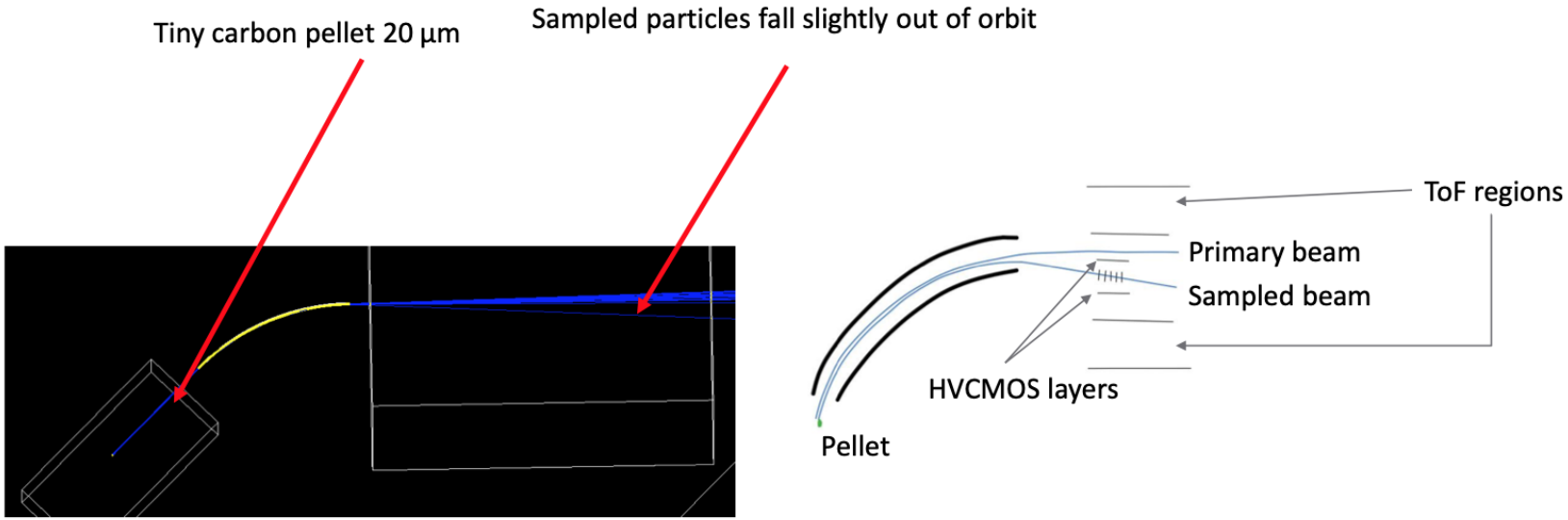




Development: low-energy polarimeter

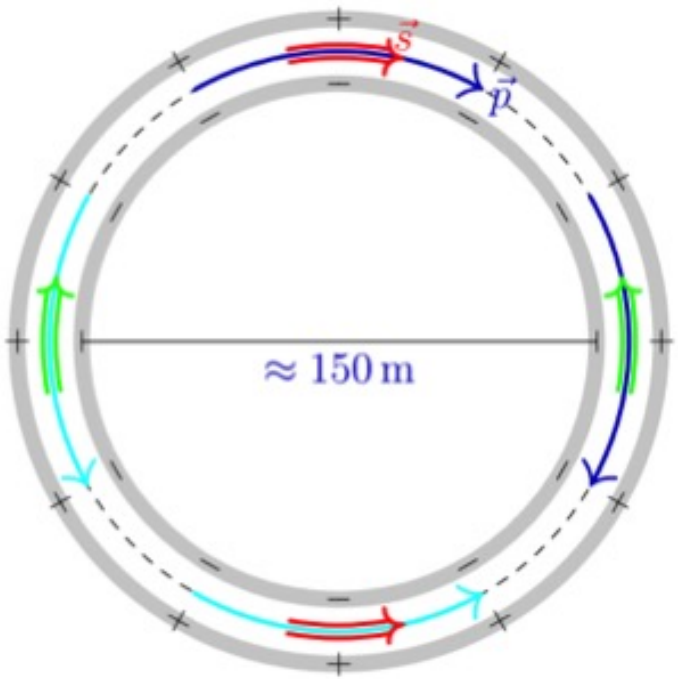
- Double scattering polarimeter
  - Carbon pellet to sample beam
  - Carbon layers to measure polarization of sampled particles
    - ★ Low-energy beam (35 MeV) requires multilayer Si detector
- Capable of providing the polarization profile of the beam



Stage 3: precision EDM ring

500 m circumference (with E = 8 MV/m)

- All-electric deflection
- Magic momentum for protons (p = 701 MeV/c)



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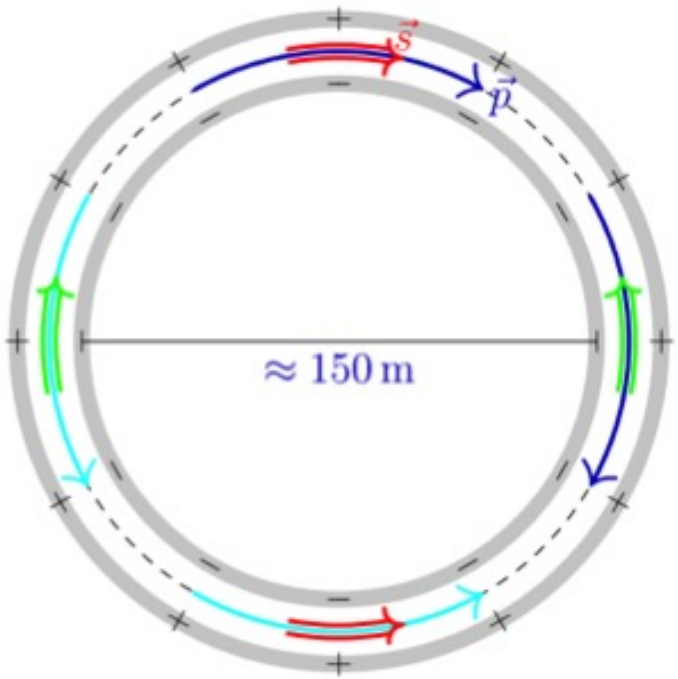

Challenges

- All-electric deflection
- 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 electrostatic ever conceived)

Conclusions

EDM searches in Storage Rings

- Outstanding scientific case with high discovery potential
- Important developments in accelerator technology

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Fundamental achievements at COSY

- Spin-control developments
- Technological systems and tools for future accelerators
- Method validation and first measurement of deuteron EDM

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- Spin-control developments
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Staged approach to face challenges in accelerator technology

- Precursor measurements at COSY
- Design of a small-scale prototype ring
- Feasibility study of a *pure electrostatic* EDM proton ring

Conclusions

EDM searches in Storage Rings

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- Feasibility study of a *pure electrostatic* EDM proton ring

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Unique chance that Europe should not miss!