Search for Electric Dipole Moments and Axions/ALPs in storage rings

Paolo Lenisa

University of Ferrara and INFN, Italy
on behalf of the JEDI Collaboration

PSTP2024

20^{th} *Workshop on Polarized Sources, Targets, and Polarimetry*

September 23^{rd}, 2024

Motivation and Methodology

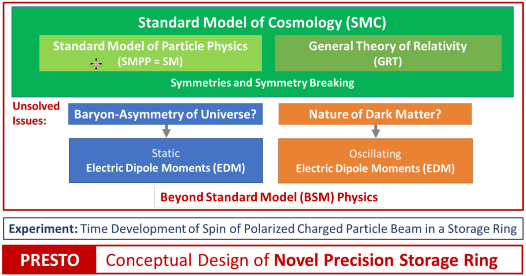
Physics case

Addressed issues

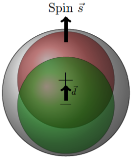
- Preponderance of matter over antimatter
- Nature of Dark Matter (DM)

Experimental approach

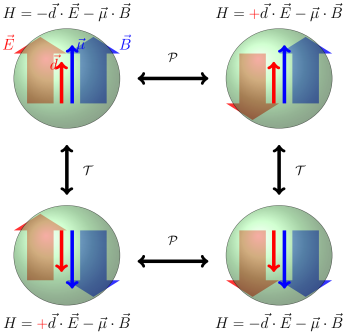
- Measurements of static Electric Dipole Moments (EDM) of fundamental particles.
- Searches for axion-like particles as DM candidates through oscillating EDM



Electric Dipole Moment (EDM)



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



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

- 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:

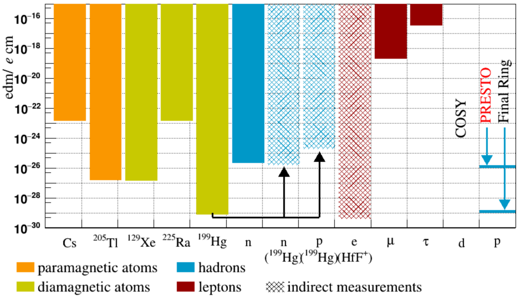
- Excess of Matter in the Universe:

	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

Static EDM upper limits



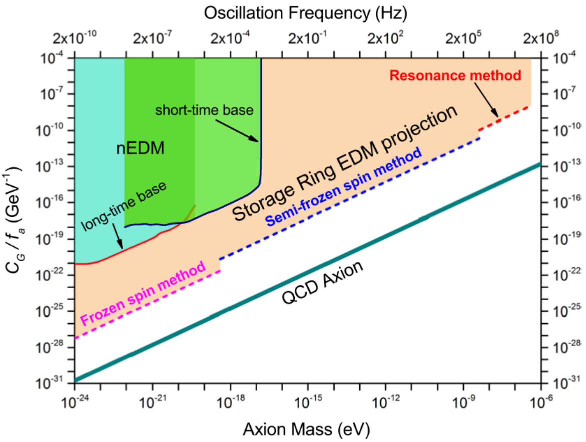
Direct EDM measurements missing

- No direct measurements of electron: limit obtained from (ThO molecule).
- No direct measurements of proton: limit obtained from ${}^{199}_{80}Hg$.
- No measurement yet of deuteron EDM.

Theory:

- EDM of single particle not suffcient to identify CP violating source

Axion Dark Matter search with Storage Ring EDM method



- Experimental limits for axion-gluon coupled oscillating EDM measurements

Spin-precession of particles with MDM and EDM

Equation of motion for spin vector $\vec{S}$

- In the rest frame of the particle

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

- Spin-precession relative to the direction of flight

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

Spin-precession of particles with MDM and EDM

Equation of motion for spin vector $\vec{S}$

- In the rest frame of the particle

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

- Spin-precession relative to the direction of flight

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

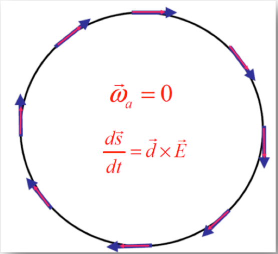
Frozen spin

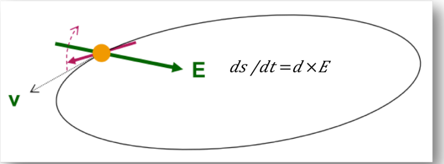
- $\vec{\Omega}_{MDM} - \vec{\Omega}_{cycl} = 0 \Rightarrow$ frozen spin (momentum and spin stay aligned)
  - Achievable with pure electric field for proton ($G > 0$): $G = \frac{1}{\gamma^2 - 1}$
  - Requires special combination of E, B fields and γ for d, ^3He ($G < 0$)

Search for static EDM in storage rings

Storage ring method to measure EDM of charged particle

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



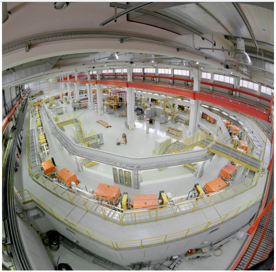


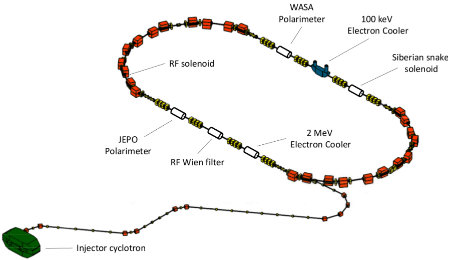
Methodologies and achievements at the COSY Storage Ring

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



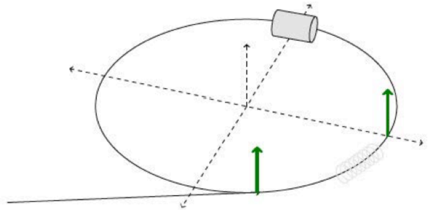


Previously used as spin-physics machine for hadron physics:

- Ideal starting point for Storage Ring EDM related R&D
- Dedicated and unique experimental effort worldwide
- Closed end 2023: essential R&D/expts. with MAGNETIC ring successfully done.

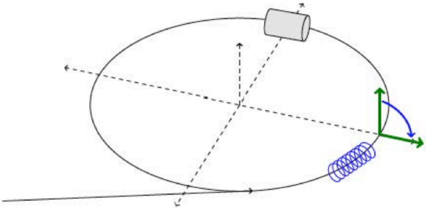
Experiment preparation

1. Inject and accelerate vertically pol. deut. to p $\approx$ 1 GeV/c



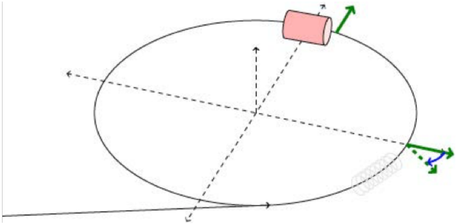
Experiment preparation

1. Inject and accelerate vertically pol. deut. to p $\approx$ 1 GeV/c
2. Flip spin with solenoid into horizontal plane



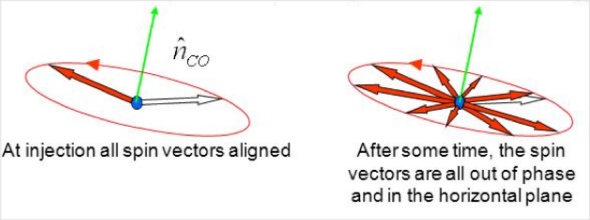
Experiment preparation

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 Carbon target
4. Measure asymmetry and determine spin precession



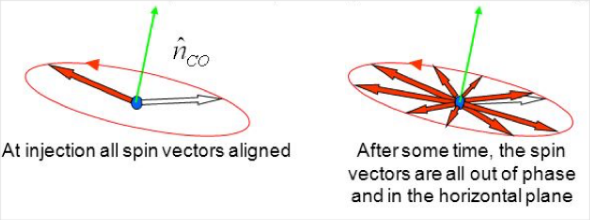
Optimization of spin-coherence time

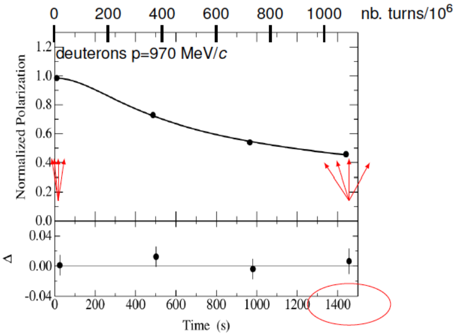
- Invariant spin axis and spin-coherence time



Optimization of spin-coherence time

- Invariant spin axis and spin-coherence time

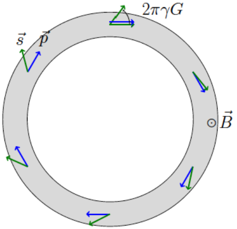




I major achievement
[Phys. Rev. Lett. 117 (2016) 054801]

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

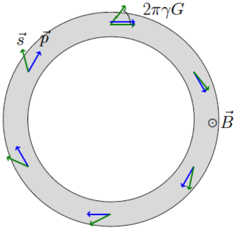
Precise determination of the spin-tune

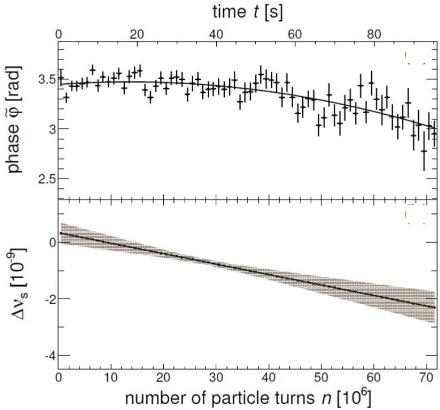


Spin-tune ν_s

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

Precise determination of the spin-tune





Spin-tune ν_s

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

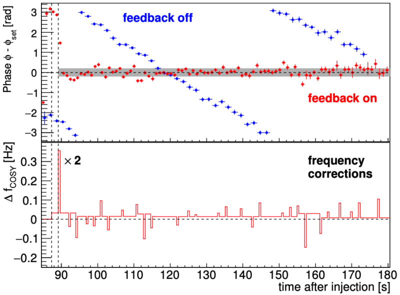
II major achievement *[Phys. Rev. Lett. 115 (2015) 094801]*

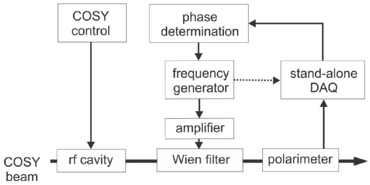
- Interpolated spin tune in 100 s:
- $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$ ($\Delta\nu_s/\nu_s \approx 10^{-10}$)
- Angle precision: $2\pi \times 10^{-10}$ = 0.6 nrad
- Previous best: 3×10^{-8} per year (g-2 experiment)
- $\rightarrow$ new tool to study systematic effects in storage rings

Phase locking spin precession in machine to device RF

Spin-feedback system maintains:

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





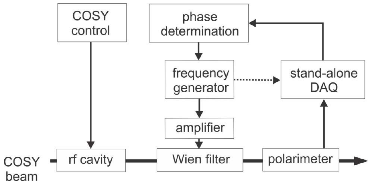
III major achievement *[Phys. Rev. Lett. 119 (2017) 014801]*:

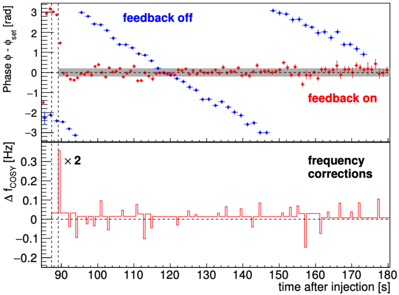
Error of phase-lock σ_ϕ = 0.21 rad

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

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

Measurements at the COSY Storage Ring

Measurement of EDM in a magnetic ring

First-ever direct EDM measurement using this method

- If external E fields = 0 spin motion is driven by radial field $\vec{E} = c\vec{\beta} \times \vec{B}$ induced by relativistic motion in the vertical $\vec{B}$ field, so that $\frac{d\vec{S}}{dt} \propto \vec{d} \times \vec{E}$
- But this yields only small oscillation of vertical component p_y due to EDM.

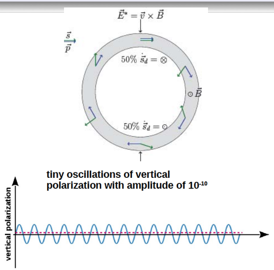
Measurement of EDM in a magnetic ring

First-ever direct EDM measurement using this method

- If external E fields = 0 spin motion is driven by radial field $\vec{E} = c\vec{\beta} \times \vec{B}$ induced by relativistic motion in the vertical $\vec{B}$ field, so that $\frac{d\vec{S}}{dt} \propto \vec{d} \times \vec{E}$
- But this yields only small oscillation of vertical component p_y due to EDM.

Problem

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



Measurement of EDM in a magnetic ring

First-ever direct EDM measurement using this method

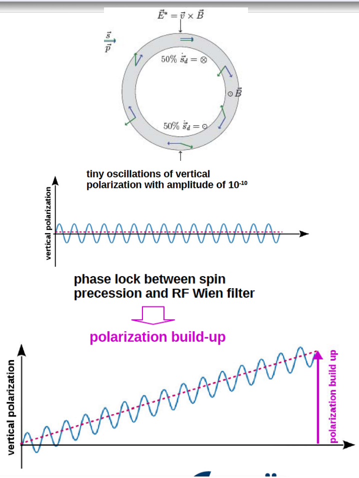
- If external E fields = 0 spin motion is driven by radial field $\vec{E} = c\vec{\beta} \times \vec{B}$ induced by relativistic motion in the vertical $\vec{B}$ field, so that $\frac{d\vec{S}}{dt} \propto \vec{d} \times \vec{E}$
- But this yields only small oscillation of vertical component p_y due to EDM.

Problem

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

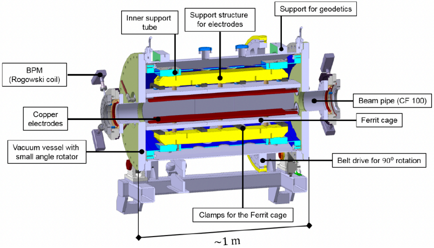
Solution: RF-Wien filter

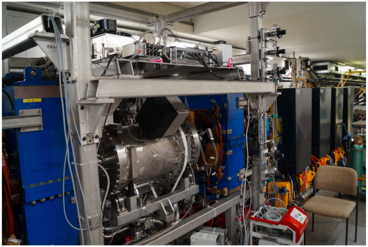
- Lorentz force: $\vec{F_L} = q(\vec{E} + \vec{v} \times \vec{B})$ = 0
- $\vec{B}$ = (0, B_y, 0) and $\vec{E}$ = (E_x, 0, 0)



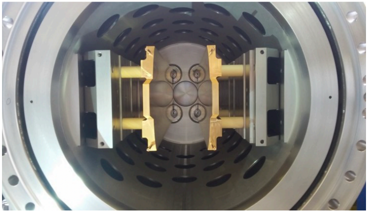
Measurement of EDM in a magnetic ring

Design of an RF-Wien filter[1]





- Waveguide provides $\vec{E} \times \vec{B}$ by design.
- Minimal $\vec{F_L}$ by careful electromagnetic design of all components.



[1] Joint development with RWTH Aachen

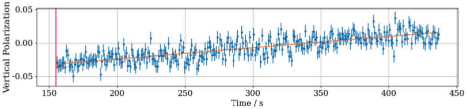
Measurement of EDM resonance strength using pilot bunch

RF Wien filter mapping

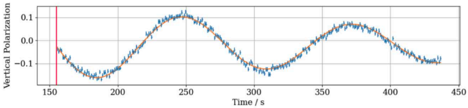
IV major achievement

- Observation of p_y (t) with two stored bunches: pilot bunch and signal bunch
  - Pilot bunch shielded from Wien-fillter RF by fast RF switches
  - Pilot bunch → unperturbed spin prec. (co-magnetometer) (subm. to PRL)
  - Signal bunch → enhanced signal (RF Wien-filter on resonance)

- Pilot bunch

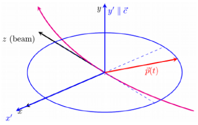


- Signal bunch

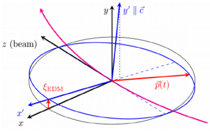


- No oscillations in pilot bunch.
- Decoherence visible in signal bunch.

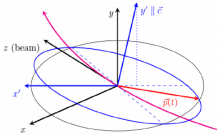
Effect of EDM and misalignments on invariant spin axis



EDM absence



EDM effect



Magnetic misalignm.

$$\phi_{EDM} = \arctan\left(\frac{\eta_{EDM}\beta}{2G}\right)$$

$$\vec{n}_{ISA} \approx \begin{pmatrix} \phi_{EDM} + \phi_{Ring} \\ 1 \\ \xi_{Ring} \end{pmatrix}$$

EDM + magnetic misalignments tilt the invariant spin axis

- Presence of EDM $\rightarrow \phi_{EDM} > 0$
- Presence of magnetic misaligments $\rightarrow \phi_{EDM}$ & $\xi_{ring} > 0$
  - $\rightarrow$ spin precess around the $\vec{n}_{ISA}$ axis
  - $\rightarrow$ oscill. vert. polarization $p_y(t)$

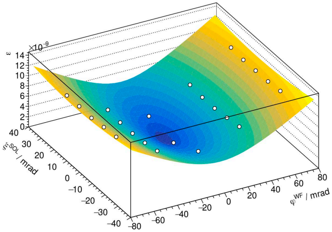
Results from dEDM precursor experiment

EDM resonance strength map for ϵ^{EDM}

- Includes tilts of invariant spin axis due to EDM and magnetic ring imperfections.

Preliminary result on static EDM

- Determination of minimum via fit with theoretical surface function yields:
  - ϕ_0^{WF} (mrad) = - 2.05 $\pm$0.02
  - ψ_0^{sol} (mrad) = + 4.32 $\pm$0.06



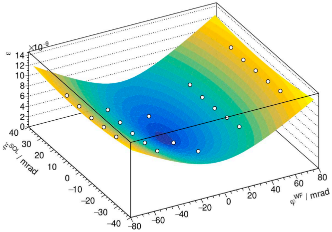
Results from dEDM precursor experiment

EDM resonance strength map for ϵ^{EDM}

- Includes tilts of invariant spin axis due to EDM and magnetic ring imperfections.

Preliminary result on static EDM

- Determination of minimum via fit with theoretical surface function yields:
  - ϕ_0^{WF} (mrad) = - 2.05 $\pm$0.02
  - ψ_0^{sol} (mrad) = + 4.32 $\pm$0.06



Extraction of EDM

1. Minimum determines spin rotation axis (3-vector) at RF WF, including EDM
2. Spin tracking in COSY lattice $\rightarrow$ orientation of stable spin axis w/o EDM
3. EDM is obtained from the difference of 1. and 2.

EDM analysis presently focused on systematics

- Data analysis close to final & EDM results in preparation.
- Goal: Describe observed tilts of stable spin axis by spin tracking

Measurement of axion-like particle in storage ring

First-ever search for axion-like particles using this method

Axions and oscillating EDM

- Axion: candidates for light dark matter ($m_a < 10^{-6}$ eV)
- 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 with freq. related to mass: $\hbar\omega_a = m_a c^2$

Measurement of axion-like particle in storage ring

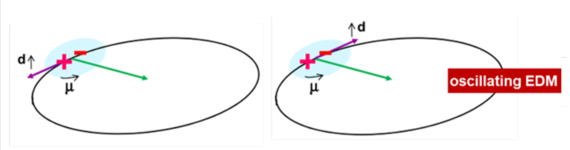
First-ever search for axion-like particles using this method

Axions and oscillating EDM

- Axion: candidates for light dark matter ($m_a < 10^{-6}$ eV)
- 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 with freq. related to mass: $\hbar\omega_a = m_a c^2$

Experimental approach

- Mag. dipole moment (MDM) $\rightarrow$ spin prec. in B field $\rightarrow$ nullifies static EDM effect
- Osc. EDM resonant condition ($\omega_a = \omega_s$) $\rightarrow$ buildup of out-of-plane spin rotation



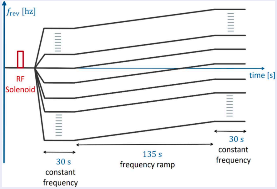
$$\vec{d} = \eta \frac{q\hbar}{2mc}\vec{S}$$

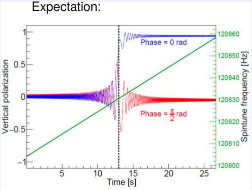
$$\eta = \eta_0 + \eta_1 \sin(\omega_{\text{axion}} t + \varphi_a)$$

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

Experiment at COSY

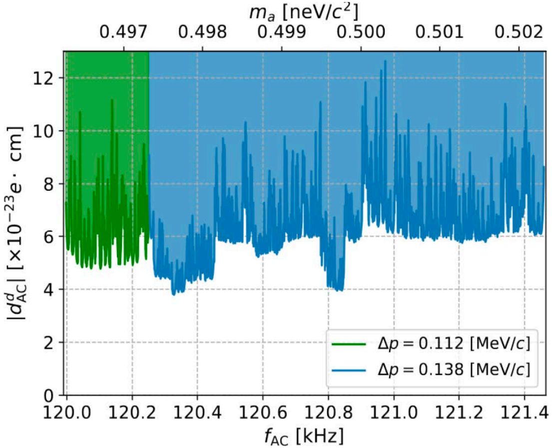
Momentum ramps (f_{rev}) searching for polarization changes





- Organization of frequency ramps.
- Jump of vertical polarization when resonance is crossed, for $\omega_a = \omega_s$

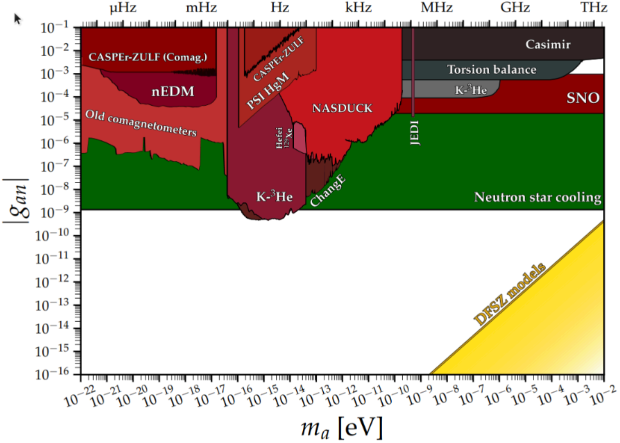
Bound on oscillating EDM of deuteron



Observed oscillation amplitudes from 4 bunches

- 90 % CL upper limit on the ALPs induced oscillating EDM
- Average of individual measured points $d_{AC} < 6.4 \times 10^{-23}$ e cm

Bound on axion-nucleon coupling



Limits on axion/ALP neutron coupling from the Particle Data Group

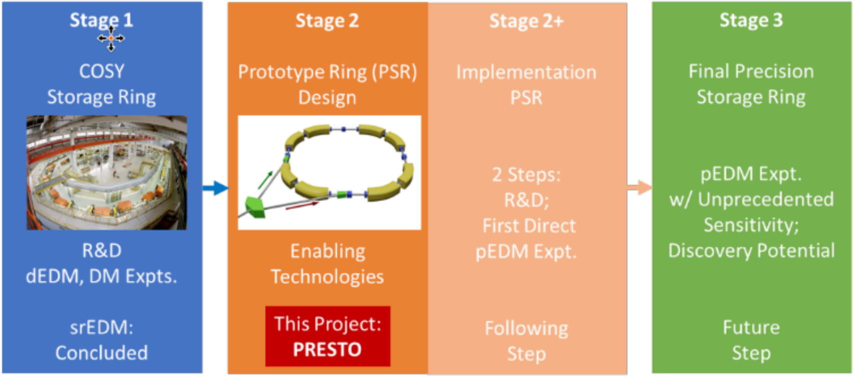
- It includes the result from the JEDI collaboration
  - S. Karanth et al., Phys. Rev. X 13 (2023) 031004

Next steps

Objective: construction of a dedicated SR for EDM studies

Possible approaches

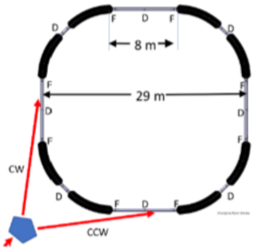
- Staged approach
- One step approach



Stage 2: prototype EDM storage ring

100 m circumference

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



Challenges

- All electric & E-B combined deflection
- Storage time
- CW-CCW operation → next slide
  - Orbit control
  - Control of orbit difference
- Polarimetry
- Spin-coherence time
- Magnetic moment effects
- Stochastic cooling

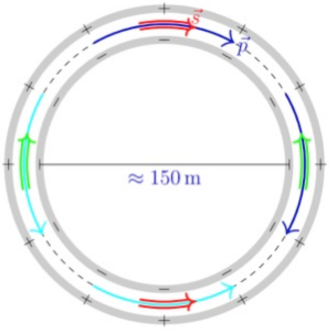
Objectives of PTR

- Study open issues.
- First direct proton EDM measurement.

Stage 3: precision EDM ring

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

- All-electric deflection
- Magic momentum for protons (p = 707 MeV/c)



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 B_r fields

"Holy Grail" storage ring (largest electrostatic ever conceived)

Conclusions

EDM searches in Storage Rings

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

Fundamental achievements at COSY

- Spin-control tools
- First measurement of (static and oscillating) deuteron EDM

Next steps

- Feasibility study of a *pure electrostatic* EDM proton ring
- Possible approches
  - Staged approach
  - Direct approach

Conclusions

EDM searches in Storage Rings

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

Fundamental achievements at COSY

- Spin-control tools
- First measurement of (static and oscillating) deuteron EDM

Next steps

- Feasibility study of a *pure electrostatic* EDM proton ring
- Possible approches
  - Staged approach
  - Direct approach

Excellent opportunity

- Interdisciplinary impact
  - Fundamental and particle physics
  - Astroparticle and hadron physics
  - Accelerator and data science

Selected publications

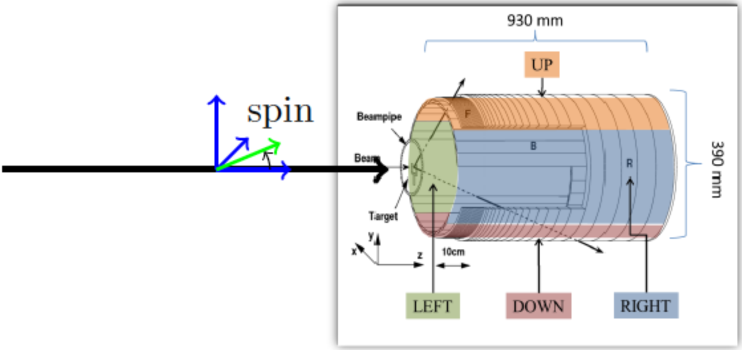
- D. Eversmann et al (JEDI Collaboration): New method for a continuous determination of the spin tune in storage rings and implications for precision experiments - Phys. Rev. Lett. 115, 094801 (2015)
- J. Slim, et al.:Electromagnetic simulation and design of a novel waveguide rf-Wien filter for electric dipole moment measurements of protons and deuterons - Nucl. Instr. and Meth. A: 828, 116 (2016), ISSN 0168-9002
- G. Guidoboni et al. (JEDI Collaboration): How to reach a thousand-second in-plane polarization lifetime with 0:97 Gev/c deuterons in a storage ring - Phys. Rev. Lett. 117, 054801 (2016)
- N. Hempelmann et al. (JEDI Collaboration): Phase locking the spin precession in a storage ring - Phys. Rev. Lett. 119, 014801 (2017)
- F. Abusaif (CPEDM Collaboration): Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study - (CERN, Geneva, 2021)
- S. Karanth et al. (JEDI Collaboration): First Search for Axion-Like Particles in a Storage Ring Using a Polarized Deuteron Beam - S. Karanth et al., Phys. Rev. X 13 (2023) 031004.
- J. Slim, et al. (JEDI Collaboration): Proof-of-principle demonstration of a pilot bunch comagnetometer in a stored beam - J. Slim et al., submitted to Phys. Rev. Lett.

Spare slides

Polarimeter

Spin-dependent elastic deuteron-carbon scattering

- Up/Down asymmetry $\propto$ *horizontal polarization*
  - $N_{up,down} \propto 1 \pm \frac{3}{2} p_z A_y sin(\nu_s \omega_{rev} t)$
  - p_d = 1 GeV/c ($\gamma_d = 1.13$) $\Rightarrow \nu_s = \gamma G \simeq$ - 0.161 (spin-tune)
  - f_{rev} = 781 kHz
- Left/Right asymmetry $\propto$ *vertical polarization* $\rightarrow$ d



Time-stamp system

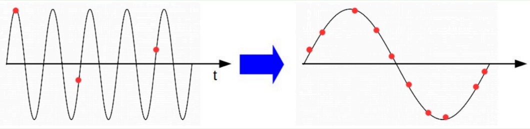
$$\text{Asymmetry: } \epsilon = \frac{N_{up} - N_{down}}{N_{up} + N_{down}} = p_z A_y \sin\left(2\pi \cdot \nu_s \cdot n_{turns}\right)$$

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

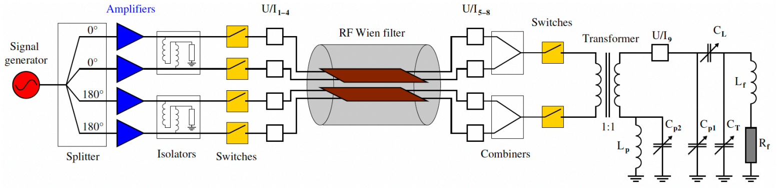
Solution: map many event to one cycle

- 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



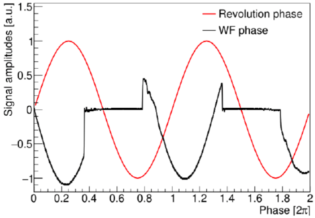
Implementation of fast switches[2] at RF Wien filter

Modification of driving circuit



GaN HEM FET-based solution:

- Short switch on/off times (≈ few ns).
- High power capabilities (≈ few kV).
- On board power damping (- 30 dB)
- Symmetric switch on/off times (≈ ns).



Switches

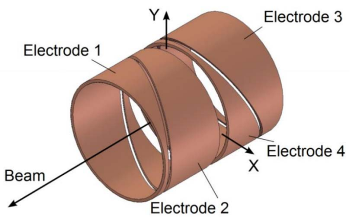
- Capable to handle up to 200 W each
- Permits system to run near a total power of 0.8 kW in pulsed mode

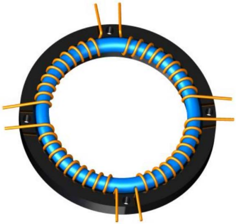
[1] Developed together with Fa. barthel HF-Technik GmbH, Aachen

Measurement of EDM in a magnetic ring

Beam position monitors for srEDM experiments

- Main adv.: short install. length (≈ 1 cm in beam direction)





Conventional BPM

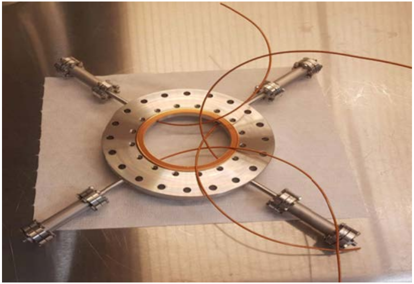
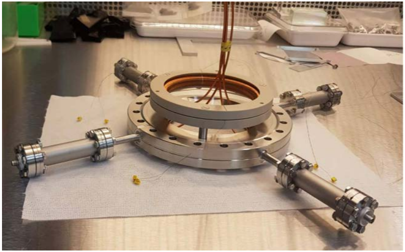
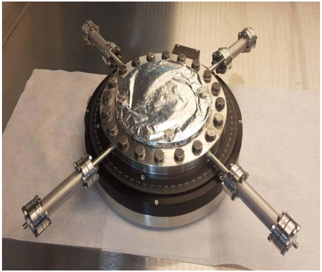
- Easy to manifacture
- Length = 20 cm
- Resolution ≈ 10 μm

Rogowski BPM (warm)

- Excellent RF-signal response
- Length = 1 cm
- Resolution ≈ 1.25 μm

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

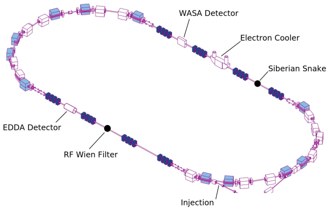
Assembly stages of one Rogowski-coil BPM

Strength of EDM resonance

EDM induced polarization oscillation

- Described by: $p_y(t) = a\ sin(\Omega^{p_y} t + \phi_{RF})$
- EDM resonance strength: ratio of Ω^{p_y} to orbital ang. frequency Ω^{rev}: $\epsilon^{EDM} = \frac{\Omega^{p_y}}{\Omega^{rev}}$



Methodology of EDM measurement

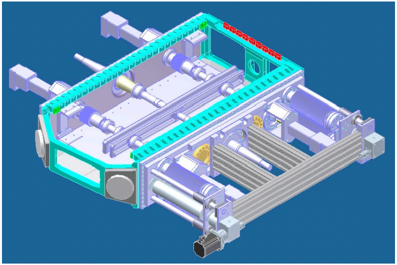
Two features simultaneously applied in the ring:

1. RF Wien-filter rotated by a small angle $\rightarrow$ generates small radial magnetic RF-field $\rightarrow$ affects the spin evolution.
2. In addition: longitudinal magnetic field in ring opposite to Wien-flter, about which spins rotate as well

Concept of EDM measurement

- Determination of the invariant spin axis
- Deduce upper limit for deuteron EDM

E/B deflector development using real-scale lab setup



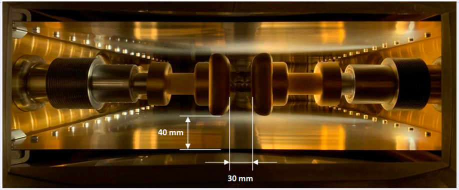
Equipment:

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

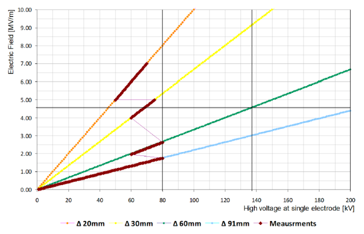
Parameters:

- Electrode length = 1020 mm
- Electrode height = 90 mm
- Electrode spacing = 20 to 80 mm
- Max. applied voltage = $\pm$ 200 kV
- Material: Aluminum coated by TiN

Results



- Electrodes at the distance of 30 mm inside the vacuum chamber



- Electric field between the electrodes vs displacement.

- Measurement procedure shortened due to time constraints.
- Max. electric field strength: 7 MV/m with 60 mm spacing between electrodes
- $\rightarrow$ Next step: setup moved to BNL?