Search for Electric Dipole Moments and Axions/ALPs of charged particles using storage rings

Paolo Lenisa

University of Ferrara and INFN, Italy
on behalf of the CP-EDM Collaboration

Joint ECFA-NuPECC-APPEC Initiative

January 13^{th}, 2023

Motivation and Methodology

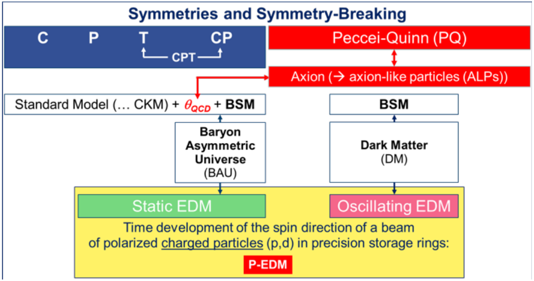
Physics case

Addressed issues

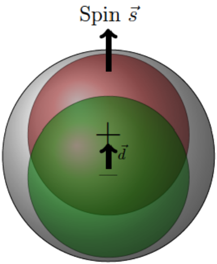
- Preponderance of matter over antimatter
- Nature of Dark Matter (DM)

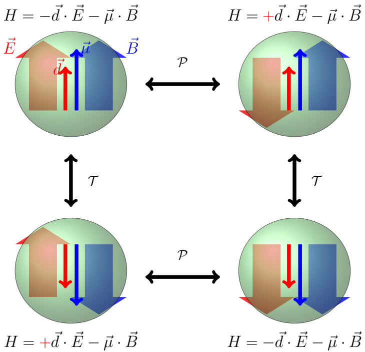
Experimental approach

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



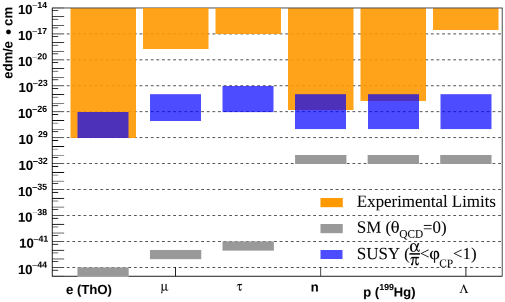
Electric Dipole Moments





- Permanent separation of + and - charge
- EDM meas. test violation of P and T symmetries ($\stackrel{CPT}{=}$CP)
- CP - violation $\Rightarrow$ one Sacharov's condition to explain Matter dominance

Static EDM upper limits



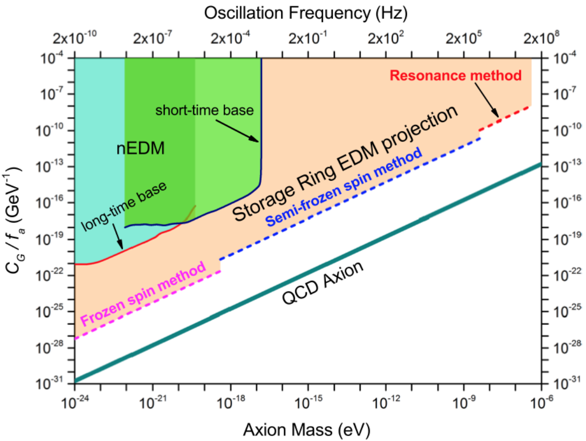
Direct EDM measurements missing

- 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

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

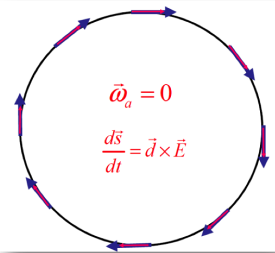
Frozen spin

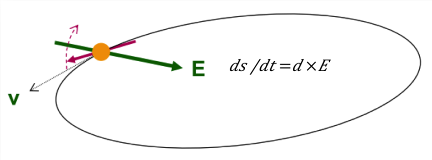
- $\vec{\Omega}_{MDM} - \vec{\Omega}_{cycl} = 0 \Rightarrow$ frozen spin (momentum and spin stay aligned)
  - Achievable with pure electric field for proton (G $>$ 0): $G = \frac{1}{\gamma^2 - 1}$
  - Requires special combination of E, B fields and γ for d, ^3He (G $<$ 0)

Search for static EDM in storage rings

Measurement concept

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

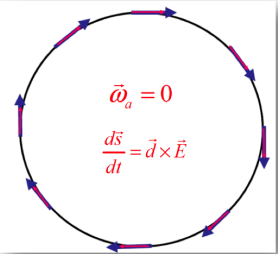


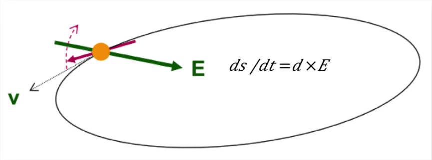


Search for static EDM in storage rings

Measurement concept

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





Storage ring method to measure EDM of charged particle

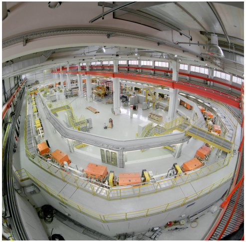
- Magic rings with spin frozen along momentum of particle.
- Polarization buildup $p_y(t) \propto$ d.

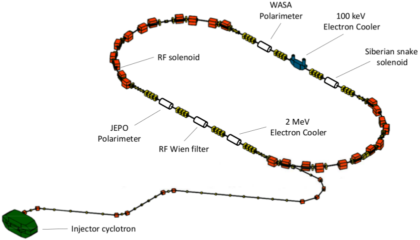
Technological achievements and new methodologies

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



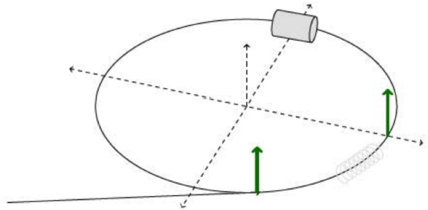


Previously used as spin-physics machine for hadron physics:

- Ideal starting point for srEDM related R&D
- Dedicated and unique experimental effort worldwide

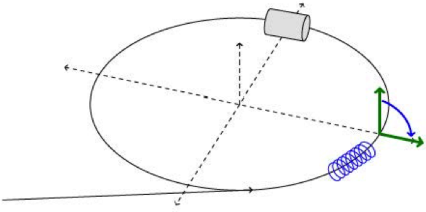
Experiment preparation

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



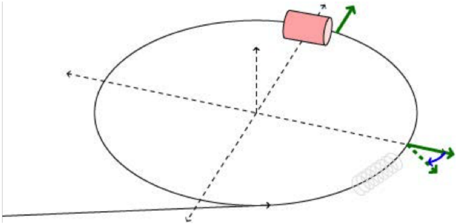
Experiment preparation

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



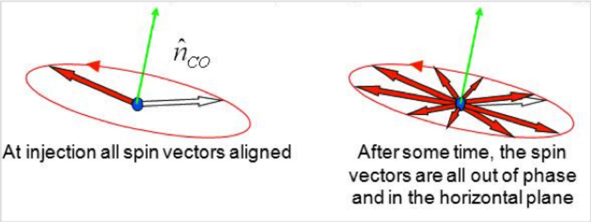
Experiment preparation

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



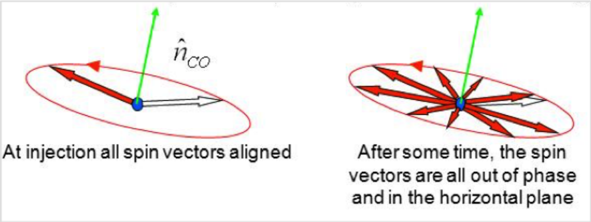
Optimization of spin-coherence time

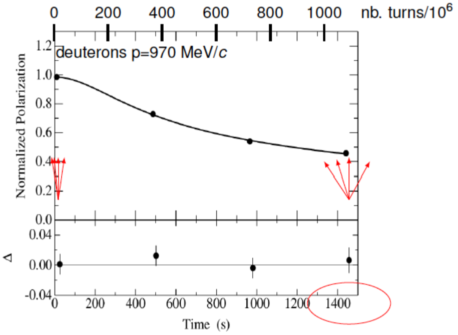
- Invariant spin axis and spin-coherence time



Optimization of spin-coherence time

- Invariant spin axis and spin-coherence time

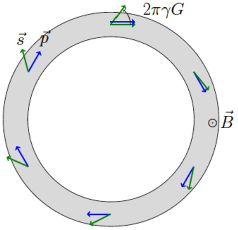




I major achievement
[Phys. Rev. Lett. 117 (2016) 054801]

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

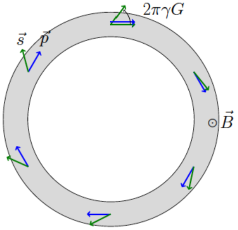
Precise determination of the spin-tune



Spin-tune ν_s

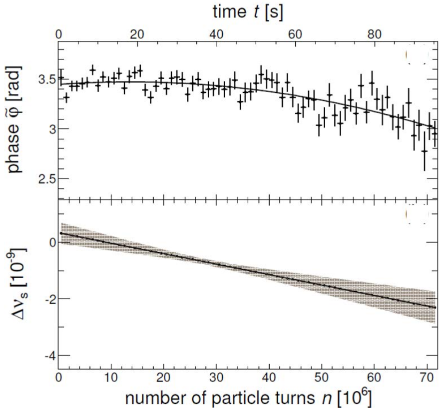
$$\nu_s = \gamma G = \frac{nb.spin-rotations}{nb.particle-revolutions}$$

Precise determination of the spin-tune



Spin-tune ν_s

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



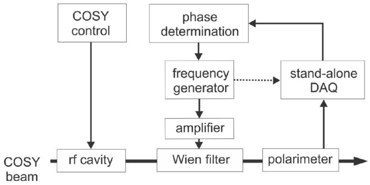
II major achievement *[Phys. Rev. Lett. 115 (2015) 094801]*

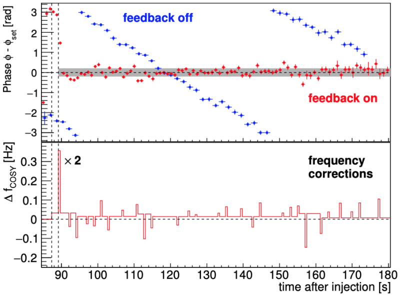
- Interpolated spin tune in 100 s:
- $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$ ($\Delta\nu_s/\nu_s \approx 10^{-10}$)
- Angle precision: $2\pi \times 10^{-10}$ = 0.6 nrad
- Previous best: 3×10^{-8} per year (g-2 experiment)
- $\rightarrow$ new tool to study systematic effects in storage rings

Phase locking spin precession in machine to device RF

Spin-feedback system maintains:

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





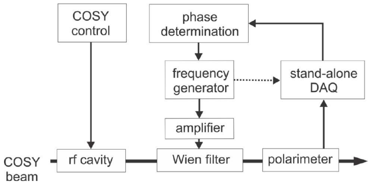
III major achievement *[Phys. Rev. Lett. 119 (2017) 014801]*:

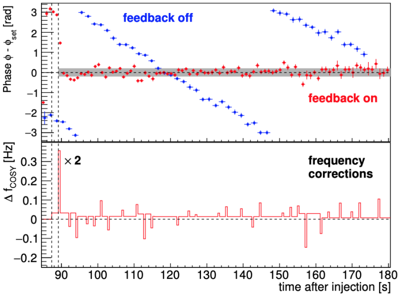
Error of phase-lock σ_ϕ = 0.21 rad

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
→ phase-locking required to achieve precision for EDM

Research achivements

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

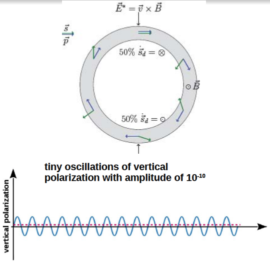
Measurement of EDM in a magnetic ring

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

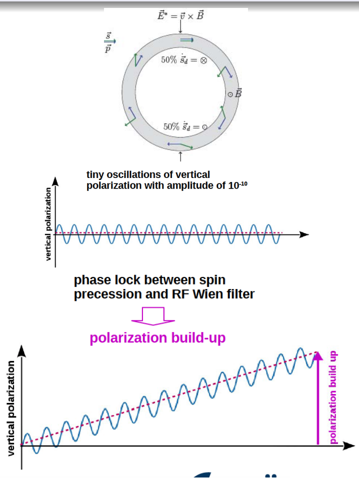
- If external E fields = 0 spin motion is driven by radial field $\vec{E} = c\vec{\beta} \times \vec{B}$ induced by relativistic motion in the vertical $\vec{B}$ field, so that $\frac{d\vec{S}}{dt} \propto \vec{d} \times \vec{E}$
- But this yields only small oscillation of vertical component p_y due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

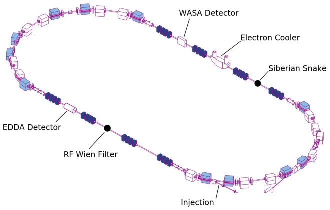
- Lorentz force: $\vec{F_L} = q(\vec{E} + \vec{v} \times \vec{B}) = 0$
- $\vec{B} = (0, B_y, 0)$ and $\vec{E} = (E_x, 0, 0)$



Strength of EDM resonance

EDM induced polarization oscillation

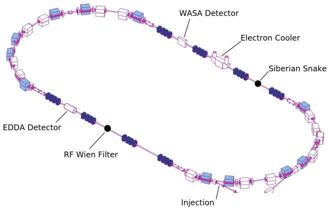
- Described by: $p_y(t) = a\, sin(\Omega^{p_y} t + \phi_{RF})$
- EDM resonance strength: ratio of Ω^{p_y} to orbital ang. frequency Ω^{rev}: $\epsilon^{EDM} = \frac{\Omega^{p_y}}{\Omega^{rev}}$



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

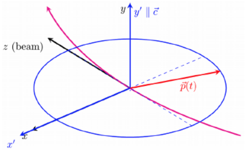
Two features simultaneously applied in the ring:

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

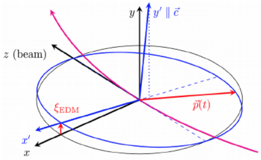
Concept of EDM measurement

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

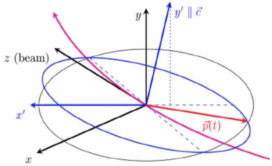
Effect of EDM and misalignments on invariant spin axis



EDM absence



EDM effect



Magnetic misalignm.

EDM tilts the invariant spin axis

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

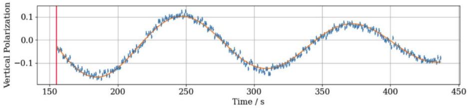
Measurement of EDM resonance strength using pilot bunch

RF Wien filter mapping

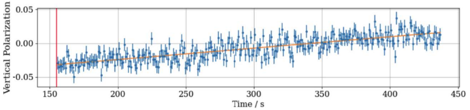
IV major achievement

- Observation of p_y (t) with two stored bunches: Signal and pilot bunch (PB)
  - Pilot bunch shielded from Wien-fillter RF by fast RF switches
  - Pilot bunch $\rightarrow$ unperturbed spin precession $\rightarrow$ RF Wien-filter on resonance
  - Pilot bunch $\rightarrow$ co-magnetometer (publication in preparation)

- Signal bunch



- Pilot bunch



- Decoherence visible in signal bunch.
- No oscillations in pilot bunch.
- Determine oscillation frequencies $\Omega^{py} \rightarrow$ Wien filter map $\epsilon^{EDM} = \frac{\Omega^{py}}{\Omega^{rev}}$

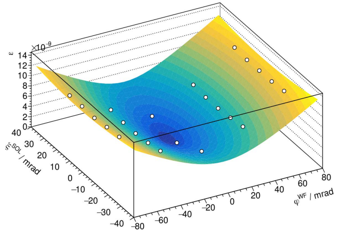
Results from dEDM precursor experiment

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



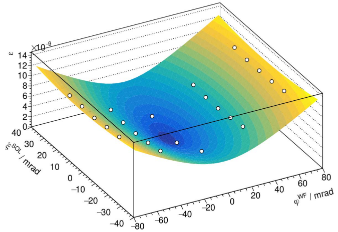
Results from dEDM precursor experiment

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

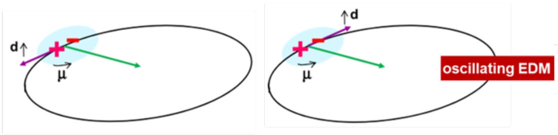
First-ever search for axion-like particles using this method

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



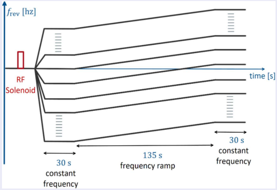
$$\vec{d} = \eta \frac{q\hbar}{2mc}\vec{S}$$

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

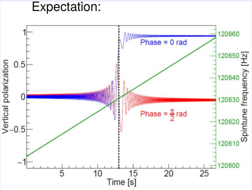
$$\omega_{\text{axion}} = \frac{m_a c^2}{\hbar}$$

Experiment at COSY

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

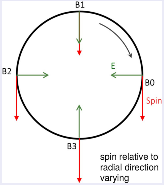


- Organization of frequency ramps.

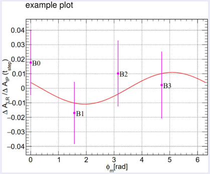


- Jump of vertical polarization when resonance is crossed, for $\omega_a = \omega_s$

Cover different oscillating EDM phases using multiple bunches

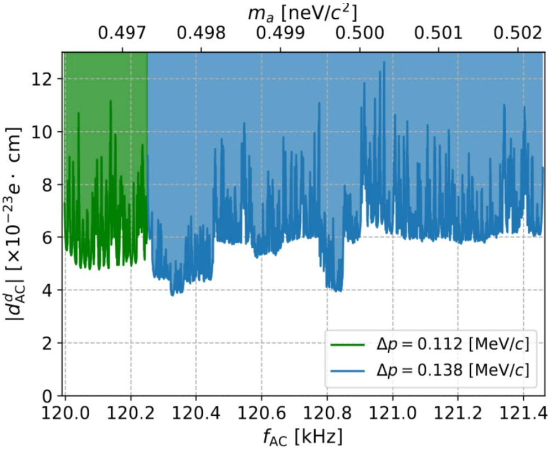


- ϕ_a not known $\rightarrow$ use perpendicular beam polarization with 4 bunches.



- LR asymmetry for one cycle and four bunches simultaneously orbiting.

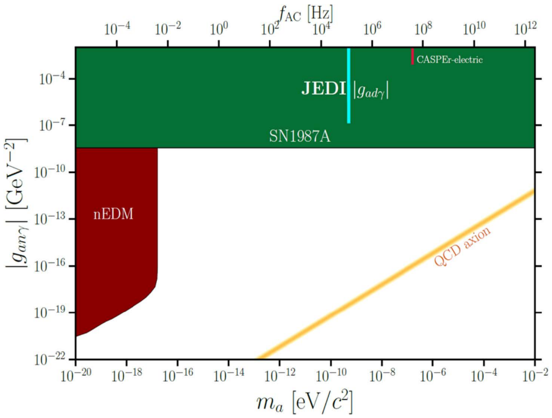
Bound on oscillating EDM of deuteron



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 ALP-EDM coupling



Coupling of ALP to deuteron EDM

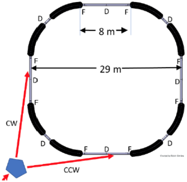
- Obtained limit of $g_{ad} < 1.7 \times 10^{-7}$ GeV^2 during few days of data taking
- Publication submitted

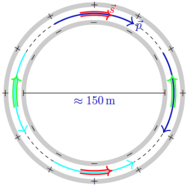
Next steps

Strategy: staged approach to a storage ring for precision physics

On the basis of the preparedness of the required technological developments

Stage 1	Stage 2	Stage 3
precursor experiment at COSY (FZ Jülich)	prototype ring	dedicated storage ring





Stage 1
- magnetic storage ring

now

Stage 2
- electrostatic storage ring
- simultaneous ↻ and ↺ beams

5 years

Stage 3
- 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}

Project stages and time frame

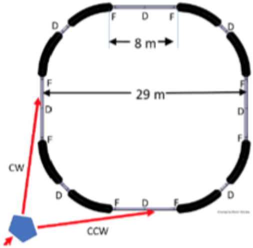
Next step: Stage 2: Prototype EDM storage ring (PTR)

Build demonstrator for charged particle EDM

- Project prepared by CPEDM working group (CERN+JEDI)
- P.B.C. process (CERN) & European Strategy for Particle Physics Update

100 m circumference

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



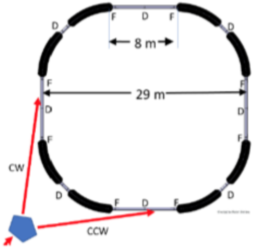
Next step: Stage 2: Prototype EDM storage ring (PTR)

Build demonstrator for charged particle EDM

- Project prepared by CPEDM working group (CERN+JEDI)
- P.B.C. process (CERN) & European Strategy for Particle Physics Update

100 m circumference

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



Challenges - open issues

- 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

Primary purpose of PTR

- Study open issues and perform first direct proton EDM measurement.

PRESTO Design Study application for PTR

Pathnder facility for a new class of PREcision-physics STOrage rings

INFRADEV-01-01-2022 - Concept Development

- Deadline: 20.04.22
- Duration: 4 years (2023-2026?)
- Budget: total 3 M €
- Coordinator + 7 beneficiaries
  - NFN (Coord.)
  - CERN
  - RWTH-Aachen
  - GSI
  - MPI-HD
  - Univ. Liverpool
  - Univ. Cracow
  - Tbilisi State University

PRESTO status

- Positive evaluation: top of reserve list
- Final decision for residual budget awaited for end of 2022
- Due to formal issues in the Referee team all the applications are re-evaluated

Summary

EDM searches in Storage Rings

- Outstaning science: high discovery potential in fundam. phys. and cosmology
- Important developments in accelerator technology

Summary

EDM searches in Storage Rings

- Outstaning science: high discovery potential in fundam. phys. and cosmology
- Important developments in accelerator technology

Technological achievements and new methodologies

- $>$ 1000 s spin-coherence time
- Precise determination of spin-tune
- Phase locking of spin-precession
- Pilot bunch method

Research achievements

- First ever measurement of deuteron EDM using a storage ring
- First-ever search for axion-like particles using a storage ring

Summary

EDM searches in Storage Rings

- Outstaning science: high discovery potential in fundam. phys. and cosmology
- Important developments in accelerator technology

Technological achievements and new methodologies

- > 1000 s spin-coherence time
- Precise determination of spin-tune
- Phase locking of spin-precession
- Pilot bunch method

Research achievements

- First ever measurement of deuteron EDM using a storage ring
- First-ever search for axion-like particles using a storage ring

Staged approach to face challenges in accelerator technology

- Design of a small-scale prototype ring
- Feasibility study of a *pure electrostatic* EDM proton ring

Summary

EDM searches in Storage Rings

- Outstaning science: high discovery potential in fundam. phys. and cosmology
- Important developments in accelerator technology

Technological achievements and new methodologies

- > 1000 s spin-coherence time
- Precise determination of spin-tune
- Phase locking of spin-precession
- Pilot bunch method

Research achievements

- First ever measurement of deuteron EDM using a storage ring
- First-ever search for axion-like particles using a storage ring

Staged approach to face challenges in accelerator technology

- Design of a small-scale prototype ring
- Feasibility study of a *pure electrostatic* EDM proton ring

Search for new funding

- PRESTO Design Study application submitted to INFRADEV-01-01-2022

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) - https://link.aps.org/doi/10.1103/PhysRevLett.115.094801
- 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 - http://www.sciencedirect.com/science/article/pii/S0168900216303710
- 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) - http://link.aps.org/doi/10.1103/PhysRevLett.117.054801
- N. Hempelmann et al. (JEDI Collaboration): Phase locking the spin precession in a storage ring - Phys. Rev. Lett. 119, 014801 (2017) - https://link.aps.org/doi/10.1103/PhysRevLett.119.014801
- F. Abusaif (CPEDM Collaboration): Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study - (CERN, Geneva, 2021), 1912.07881
- S. Karanth et al. (JEDI Collaboration): First Search for Axion-Like Particles in a Storage Ring Using a Polarized Deuteron Beam (2022) - 2208.07293.