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

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# Motivation and Methodology

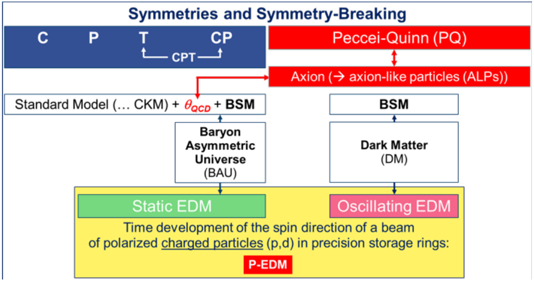
# Physics case

## Addressed issues

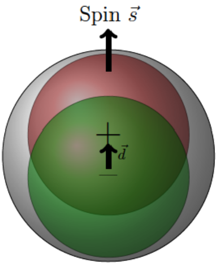
- Preponderance of matter over antimatter
- Nature of Dark Matter (DM)

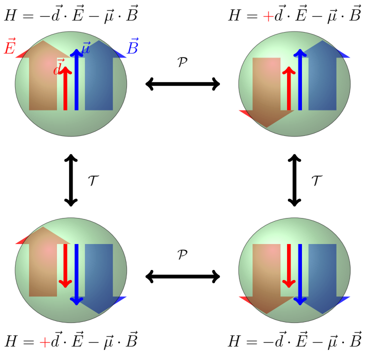
## Experimental approach

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



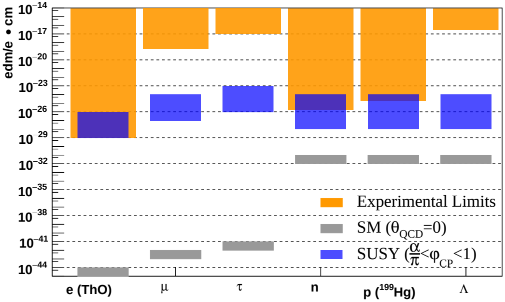
# Electric Dipole Moments




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

# Static EDM upper limits



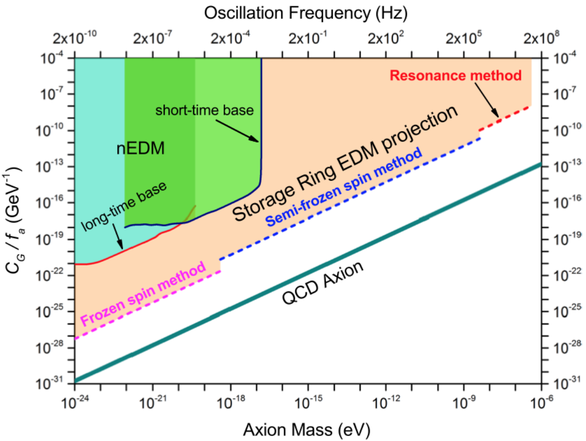

## Direct EDM measurements missing

- 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

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

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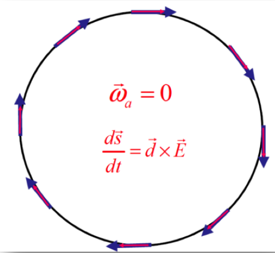
## Frozen spin

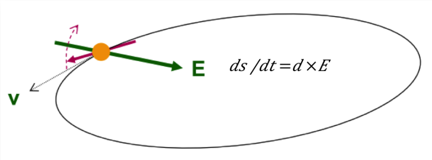
- $\vec{\Omega}_{MDM} - \vec{\Omega}_{cycl} = 0 \Rightarrow$ frozen spin (momentum and spin stay aligned)
  - Achievable with pure electric field for proton (G $>$ 0): $G = \frac{1}{\gamma^2 - 1}$
  - Requires special combination of E, B fields and $\gamma$ for d, $^3He$ (G $<$ 0)

# 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



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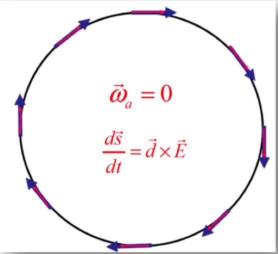
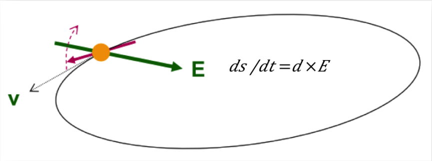



## Storage ring method to measure EDM of charged particle

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

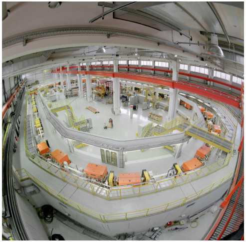
# Developments at COSY

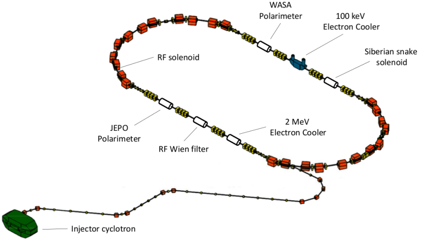
## Technological achievements and new methodologies

# 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



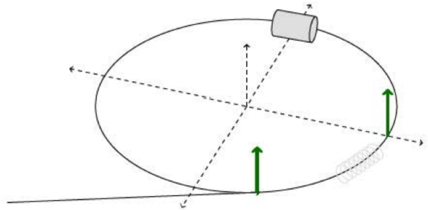



## Previously used as spin-physics machine for hadron physics:

- 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



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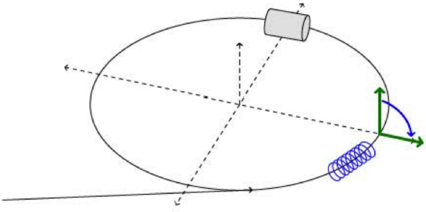
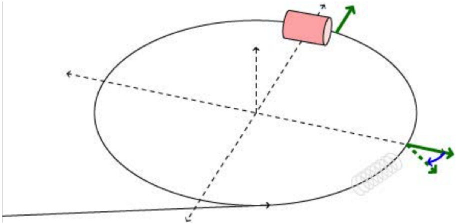


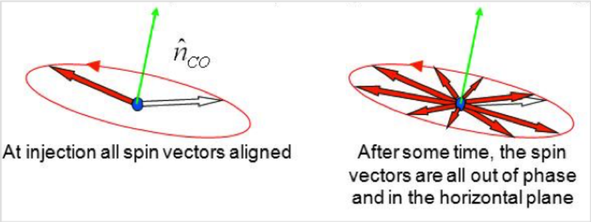
# Experiment preparation

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 Carbon target
4. Measure asymmetry and determine spin precession



# Optimization of spin-coherence time

- Invariant spin axis and spin-coherence time



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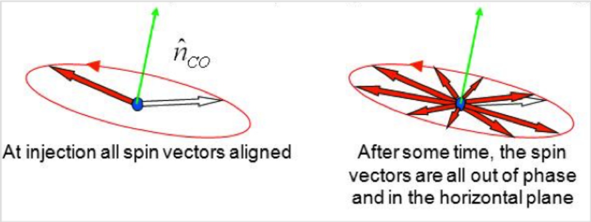
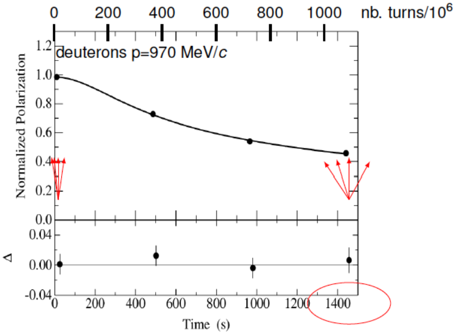
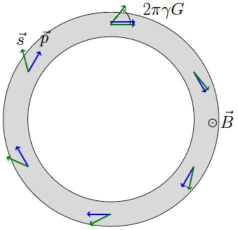



**I major achievement**
*[Phys. Rev. Lett. 117 (2016) 054801]*

- $\tau_{SCT} = (782 \pm 117)$s
- Previously: $\tau_{SCT}$(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 $\nu_s$**

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

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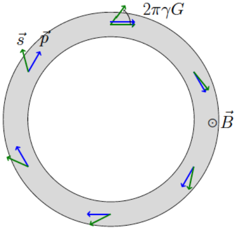
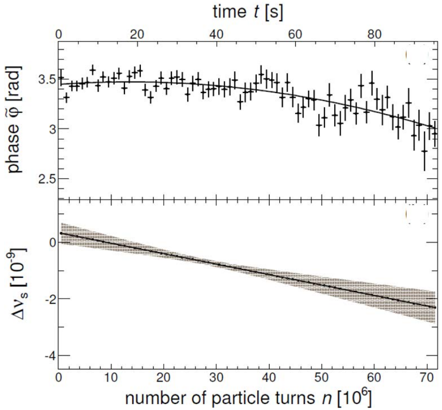



**Spin-tune $\nu_s$**

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

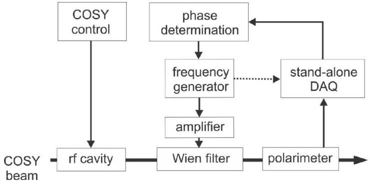
**II major achievement** *[Phys. Rev. Lett. 115 (2015) 094801]*

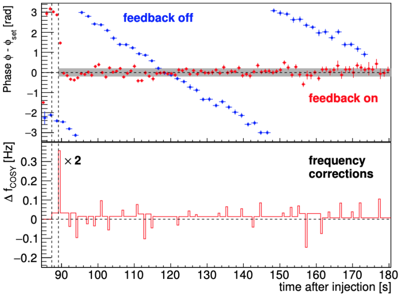
- Interpolated spin tune in 100 s:
- $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$ ($\Delta\nu_s/\nu_s \approx 10^{-10}$)
- Angle precision: $2\pi \times 10^{-10}$ = 0.6 nrad
- Previous best: $3 \times 10^{-8}$ per year (g-2 experiment)
- $\rightarrow$ new tool to study systematic effects in storage 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 $\sigma_\phi$ = 0.21 rad

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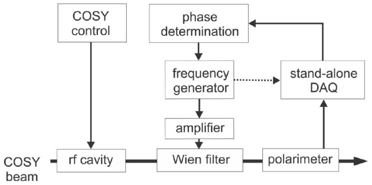


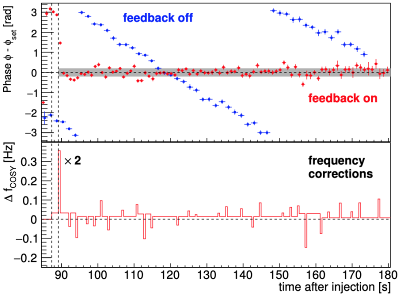


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At COSY freezing of spin precession not possible
$\rightarrow$ phase-locking required to achieve precision for EDM

# Developments at COSY

## Research achievements

# 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.

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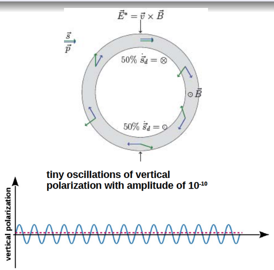
**Problem**

- Momentum ↑↑ spin
  spin ⇒ spin kicked up
- Momentum ↑↓ spin
  ⇒ spin kicked down
- ⇒ no accumulation of vert. asymmetry



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### Problem

- Momentum ↑↑ spin
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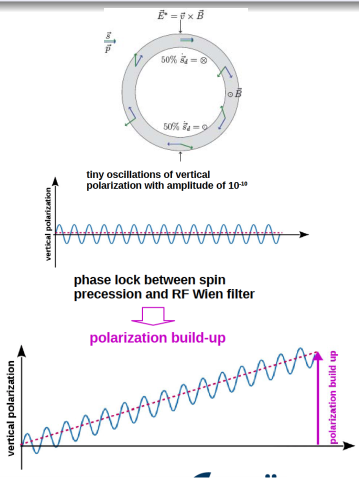
- Momentum ↑↓ spin
  ⇒ spin kicked down
- ⇒ no accumulation of vert. asymmetry

### Solution: RF-Wien filter

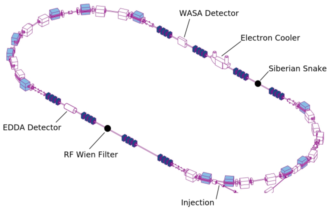
- Lorentz force: $\vec{F_L} = q(\vec{E} + \vec{v} \times \vec{B}) = 0$
- $\vec{B}$ = (0, $B_y$, 0) and $\vec{E}$ = ($E_x$, 0, 0)



# 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 $\Omega^{p_y}$ to orbital ang. frequency $\Omega^{rev}$: $\epsilon^{EDM} = \frac{\Omega^{p_y}}{\Omega^{rev}}$



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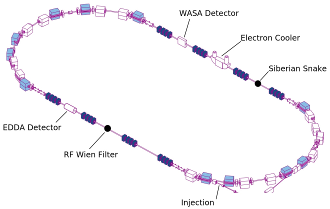



## Methodology of EDM measurement

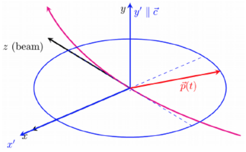
Two features simultaneously applied in the ring:

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

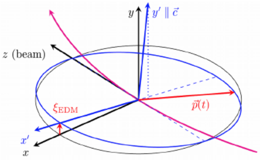
## Concept of EDM measurement

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

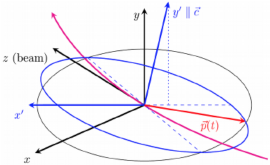
# Effect of EDM and misalignments on invariant spin axis




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 $p_y(t)$

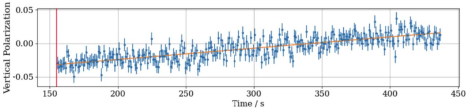
# Measurement of EDM resonance strength using pilot bunch

## RF Wien filter mapping

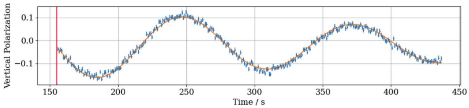
### IV major achievement

- 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
  - $\rightarrow$ unperturbed spin precession $\rightarrow$ RF Wien-filter on resonance
  - Signal bunch contains EDM signal

- Pilot bunch




- Signal bunch




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

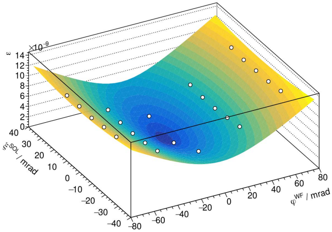
# Results from dEDM precursor experiment

## EDM resonance strength map for $\epsilon^{EDM}$

- 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:
  - $\phi_0^{WF}$ (mrad) = - 2.05 $\pm$0.02
  - $\psi_0^{sol}$ (mrad) = + 4.32 $\pm$0.06



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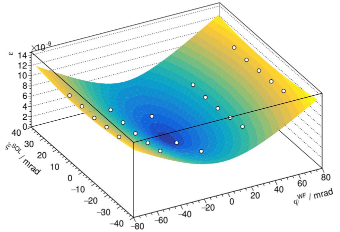


## Extraction of EDM

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-$\theta$ term
- Generation of an oscillating EDM with freq. related to mass: $\hbar\omega_a = m_a c^2$

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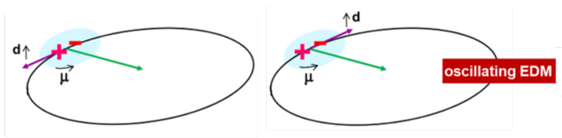
### Experimental approach

- 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



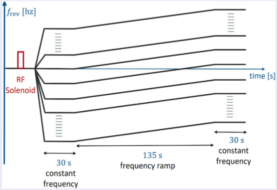

$$\vec{d} = \eta \frac{q\hbar}{2mc}\vec{S}$$

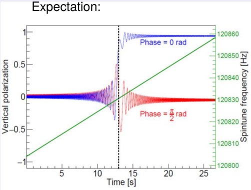
$$\eta = \eta_0 + \eta_1 \sin(\omega_{\text{axion}} t + \varphi_a)$$

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

# Experiment at COSY

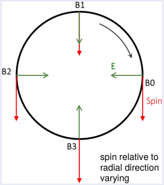
## Momentum ramps ($f_{rev}$) searching for polarization changes

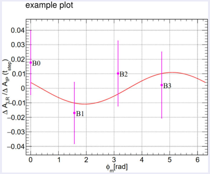



- Organization of frequency ramps.
- Jump of vertical polarization when resonance is crossed, for $\omega_a = \omega_s$

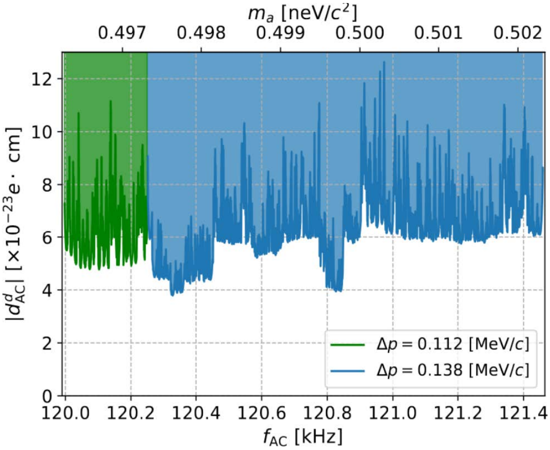
## Cover different oscillating EDM phases using multiple bunches




- $\phi_a$ not known $\rightarrow$ use perpendicular beam polarization with 4 bunches.
- LR asymmetry for one cycle and four bunches simultaneously orbiting.

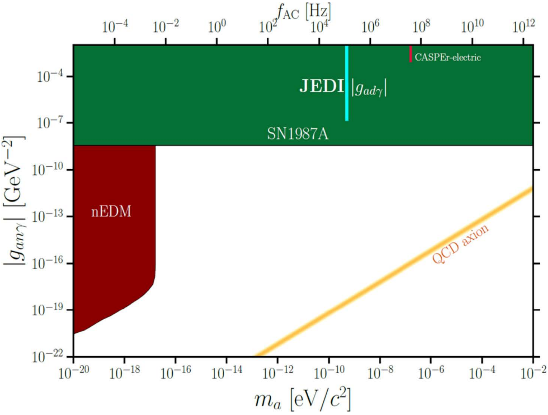
# Bound on oscillating EDM of deuteron




**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
- Accepted for publication on Phys. Rev. X

# 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

precursor experiment

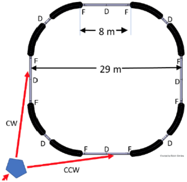
at COSY (FZ Jülich)

- magnetic storage ring

now

## Stage 2

prototype ring

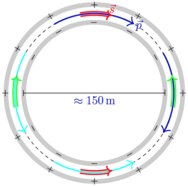



- electrostatic storage ring
- simultaneous ↻ and ↺ beams

5 years

## Stage 3

dedicated storage ring




- magic momentum

(701 MeV/$c$)

10 years

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

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

Project stages and time frame

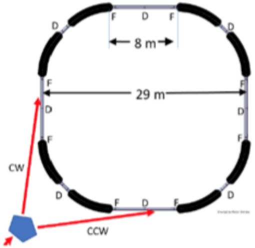
# Next step: Stage 2: Prototype EDM storage ring (PSR)

## 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



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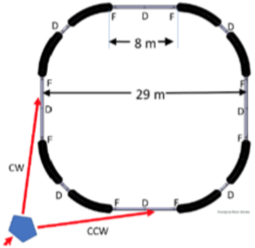


## Challenges - open issues

- 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 PSR

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

# Summary

## EDM searches in Storage Rings

- Outstaning science: high discovery potential in fundam. phys. and cosmology
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### 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

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## Staged approach to face challenges in accelerator technology

- Design of a small-scale prototype ring
- ERC-AdG submitted on 23.05.23

# 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`.