

INCH: International Network for Challenges of a Spin Physics Hadron Storage Ring

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Motivation and Methodology

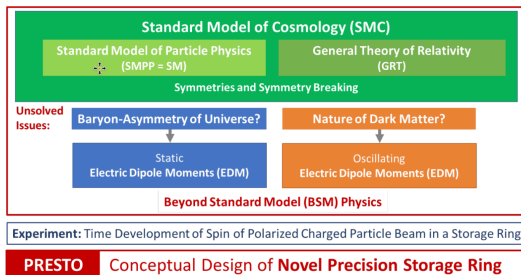
Physics case

Addressed issues

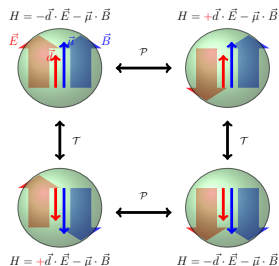
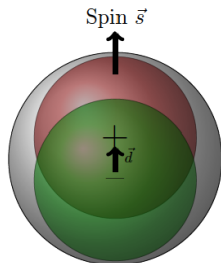
- Preponderance of matter over antimatter
- Nature of Dark Matter (DM)

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



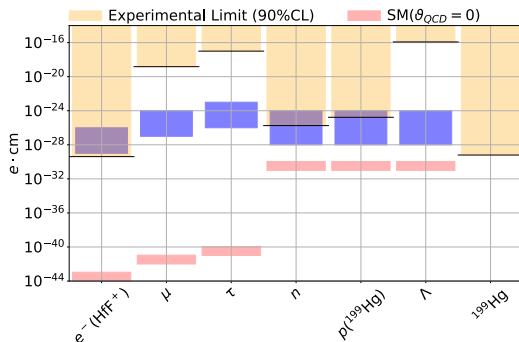
- Permanent separation of + and - charge
- EDM meas. test violation of P and T symmetries ($\stackrel{CPT}{=} \text{CP}$)
- CP - violation \Rightarrow one Sacharov's condition to explain Matter dominance

Matter dominance:

- Excess of Matter in the Universe:

	observed	SM prediction
$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$	6×10^{-10}	10^{-18}

Static EDM upper limits



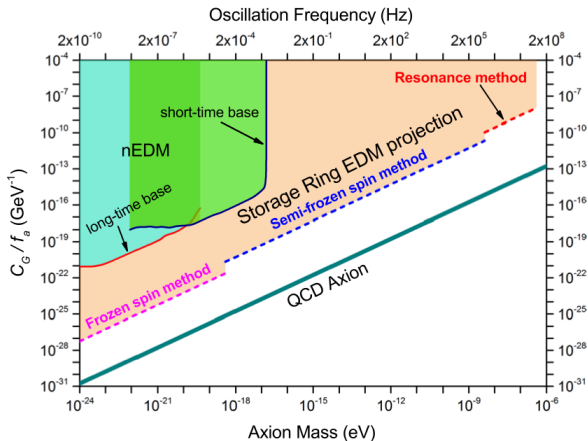
Direct EDM measurements missing

- No direct measurements of electron: limit obtained from HfF^+ molecule.
- No direct measurements of proton: limit obtained from $^{199}_{80}\text{Hg}$.
- No measurement yet of deuteron EDM.

Theory:

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

Axion Dark Matter search with Storage Ring EDM method

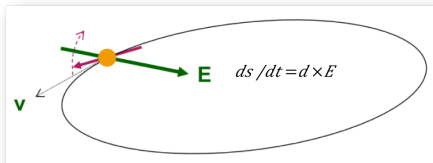
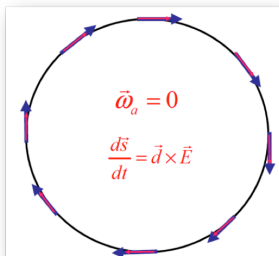


- Experimental limits for axion-gluon coupled oscillating EDM measurements

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



Search for oscillating EDM in storage rings

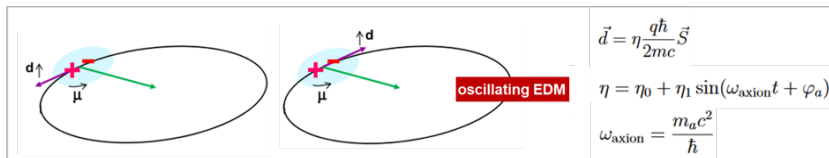
Measurement of axion-like particle in storage ring

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

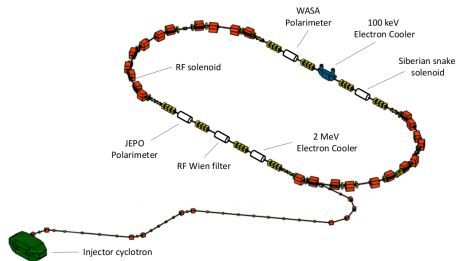
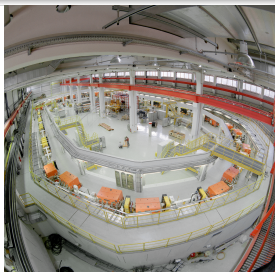


Achievements at the COSY Storage Ring

The COSY storage ring at FZ-Jülich (Germany)

COoler SYnchrotron COSY

- Cooler and storage ring for (pol.) protons and deuterons.
- Momenta $p = 0.3\text{--}3.7$ 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.

Measurement of static EDM in a magnetic ring

First-ever direct EDM measurement using this method

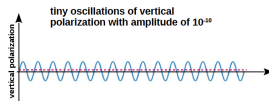
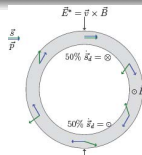
- If external E fields = 0 spin motion is driven by radial field $\vec{E} = c\vec{\beta} \times \vec{B}$ induced by relativistic motion in the vertical \vec{B} field, so that $\frac{d\vec{S}}{dt} \propto \vec{d} \times \vec{E}$
- But this yields only small oscillation of vertical component p_y due to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

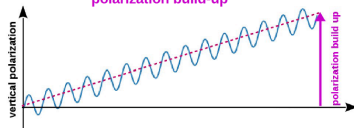
Solution: RF-Wien filter

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



phase lock between spin precession and RF Wien filter

polarization build-up



Results from dEDM precursor experiment

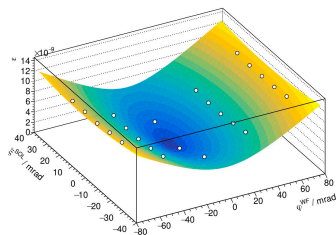
First-ever measurement of deuteron EDM

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 ± 0.02
 - ▶ ψ_0^{sol} (mrad) = $+4.32 \pm 0.06$

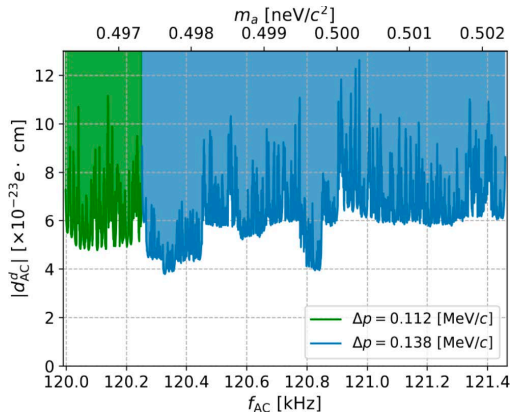


Extraction of EDM

- Minimum determines spin rotation axis (3-vector) at RF WF, including EDM
- Spin tracking in COSY lattice → orientation of stable spin axis w/o EDM
- Data analysis close to final & EDM results.
- In preparation: Determination of the invariant spin-axis in a storage ring and implications for the measurement of the deuteron EDM

Measurement of oscillating EDM in a storage ring

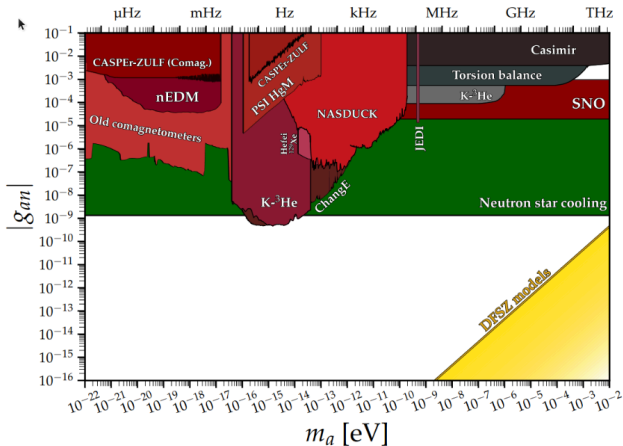
First-ever measurement using this method



Bound on oscillating EDM of deuteron

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

Bound on axion-nucleon coupling



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

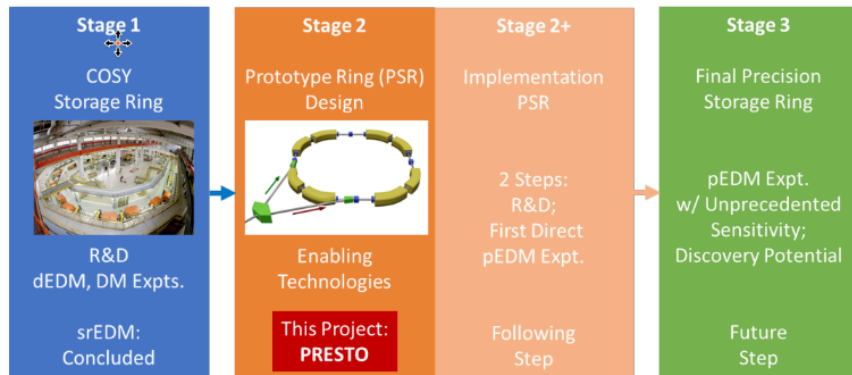
- It includes the result from the JEDI collaboration
 - ▶ S. Karanth et al., Phys. Rev. X 13 (2023) 031004

The INCH Lol

Framework: construction of a dedicated SR for EDM studies

Possible approaches

- Staged approach
- One step approach



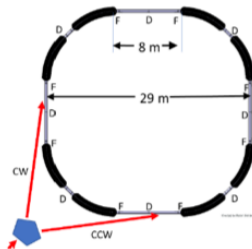
Stage 2: prototype EDM storage ring

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**
 - ▶ 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.

Challenges

Optim. of beam transport and injection efficiency with ML tools

- The project requires high-intensity polarized beams, making it essential to optimize the transport of the beam from the polarized source to the storage ring and its injection.
- This optimization is well suited for machine learning algorithms, as the beam intensity depends on hundreds of parameters, such as magnet settings.

Providing long SCT of the stored polarized beam

- Spin rotations caused by machine imperfections in particles with a magnetic dipole moment lead to the loss of in-plane polarization coherence.
- To extend spin coherence, bunched beams and 6-pole magnets are employed to mitigate decoherence effects from betatron and synchrotron oscillations.

Connection to TAs and to VAs

- Achieving the objectives of the INCH project necessitates a strong collaborative framework among INFN, CERN, RWTH, GSI, and BNL.
- INFN, RWTH, FZ-Jülich (now GSI), and CERN have already played a pivotal role in the successful experimental developments at the COSY storage ring, demonstrating the effectiveness of international cooperation.
- It is essential to strengthen ties with U.S. partners, who are likewise engaged in addressing the fundamental questions at the heart of this research.

Beneficiaries, Partners & Requests

Participating and partner institutions

- INFN - Ferrara (P.L. Coordinator)
- RWTH - Referent: J. Pretz
- GSI - Referents: Y. Litvinov/R. Assmann
- CERN - Referent: C. Carli
- BNL - Referents: Y. Semertzidis/F. Rathmann

Requests: 500 k€

- 1 Postdoc for two years + 1 PhD for INFN-FE
- 1 Postdoc for two years + 1 PhD for RWTH-Aachen
 - ▶ Joint PhD positions possible
- Travel expenses between participating and partner institutions
- *Important: keep the "unique" competence acquired by the young researchers*

Selected publications

- A. Awal et al. [Optimization of the injection beam line at the Cooler Synchrotron COSY using Bayesian Optimization](#) JINST 18 (2023) 04, P04010
- A. Awal et al. [Injection optimization at particle accelerators via reinforcement learning: From simulation to real-world application](#) Phys.Rev.Accel.Beams 28 (2025) 3, 034601
- 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)
- 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](#)

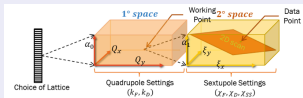
Spares

Optimization of the spin-coherence time in a dedicated ring

Spin-coherence time

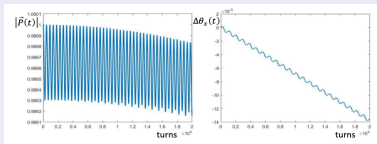
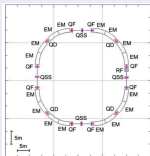
- Polarization vector of a particle ensemble: $\vec{P}(t) = \frac{1}{n} \sum_1^n \vec{s}_i(t)$
- Spin-coherence time τ : $P(\tau) = \frac{P_0}{e}$

Development of an analytical model



- Minimization of spin-tune difference three 6-pole families: $\tau \propto \frac{1}{\Delta\nu_s}$
- $$\frac{\Delta L}{L} = -\frac{\pi}{L} (\epsilon_x \xi_x + \epsilon_y \xi_y) + \alpha_0 \delta + \alpha_1 \delta^2$$
- $$= \alpha_1 \delta^2 - \frac{\pi}{L} \epsilon_x \xi_x - \frac{\pi}{L} \epsilon_y \xi_y$$
- $\Delta\nu_s \propto \frac{\Delta L}{L} \equiv \text{path lengthening}$

Validation of the model by B-mad simulations



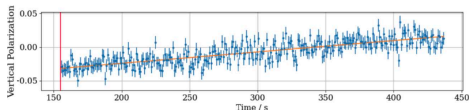
Measurement of EDM resonance strength using pilot bunch

RF Wien filter mapping

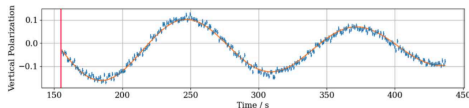
IV major achievement [*Phys. Rev. Research* 7, 023257]

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

● Pilot bunch



● Signal bunch

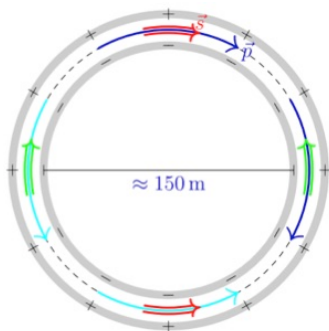


- No oscillations in pilot bunch.
- Decoherence visible in signal bunch.

Stage 3: precision EDM ring

500 m circumference (with $E = 8 \text{ MV/m}$)

- All-electric deflection
- Magic momentum for protons ($p = 707 \text{ MeV/c}$)



Challenges

- All-electric deflection
- Simultaneous CW/CCW beams
- Phase-space cooled beams
- Long spin coherence time ($> 1000 \text{ s}$)
- 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)