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

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Town Meeting - Hadron Physics in Horizon Europe

July 2^{nd}, 2025

Motivation and Methodology

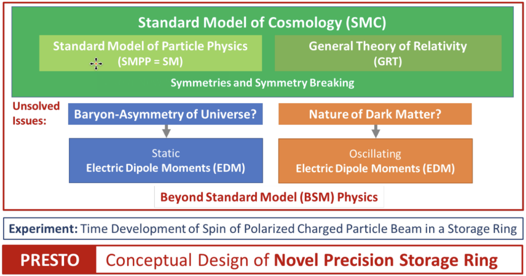
Physics case

Addressed issues

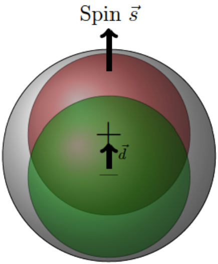
- Preponderance of matter over antimatter
- Nature of Dark Matter (DM)

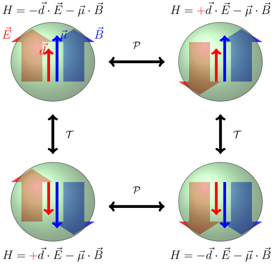
Experimental approach

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



Electric Dipole Moments





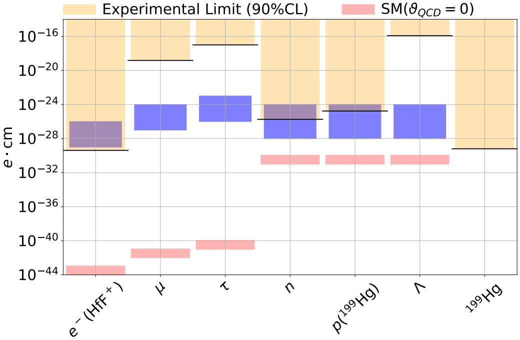
- Permanent separation of + and - charge
- EDM meas. test violation of P and T symmetries ($\stackrel{CPT}{=}$CP)
- CP - violation $\Rightarrow$ one Sacharov's condition to explain Matter dominance

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}

Static EDM upper limits



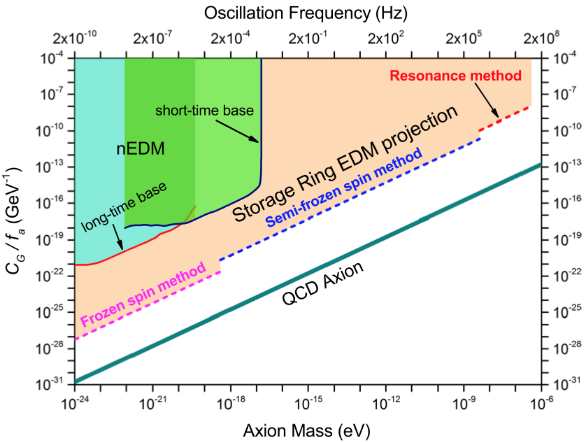
Direct EDM measurements missing

- No direct measurements of electron: limit obtained from HfF^+ molecule.
- No direct measurements of proton: limit obtained from $^{199}_{80}Hg$.
- 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

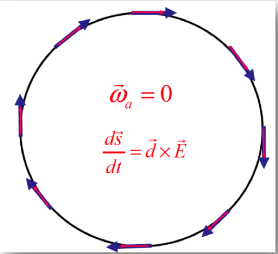


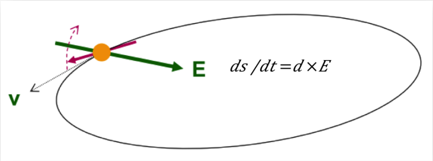
- Experimental limits for axion-gluon coupled oscillating EDM measurements

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

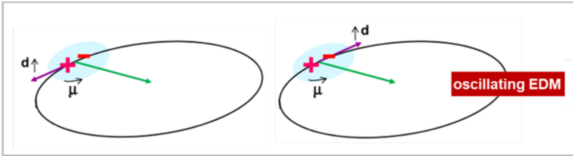
Measurement of axion-like particle in storage ring

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



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

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

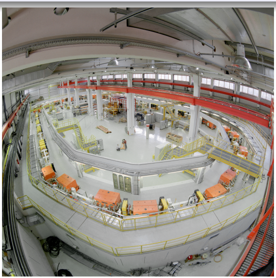
$$\omega_{\text{axion}} = \frac{m_a c^2}{\hbar}$$

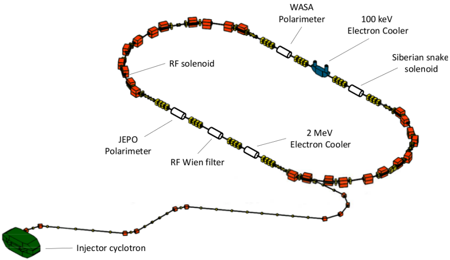
Achievements at the COSY Storage Ring

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.

Measurement of static EDM in a magnetic ring

First-ever direct EDM measurement using this method

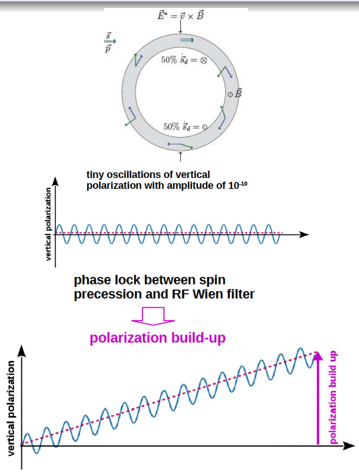
- If external E fields = 0 spin motion is driven by radial field $\vec{E} = c\vec{\beta} \times \vec{B}$ induced by relativistic motion in the vertical $\vec{B}$ field, so that $\frac{d\vec{S}}{dt} \propto \vec{d} \times \vec{E}$
- But this yields only small oscillation of vertical component p_y due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



Results from dEDM precursor experiment

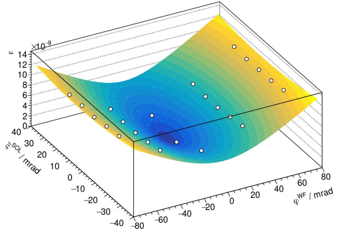
First-ever measurement of deuteron EDM

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



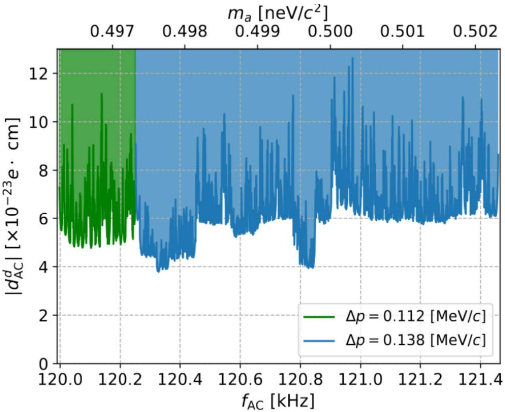
Extraction of EDM

- Minimum determines spin rotation axis (3-vector) at RF WF, including EDM
- Spin tracking in COSY lattice $\rightarrow$ 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

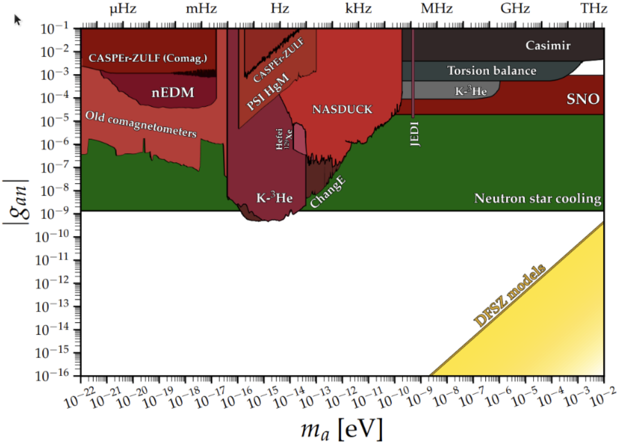
First-ever measurement using this method



Bound on oscillating EDM of deuteron

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

Bound on axion-nucleon coupling



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

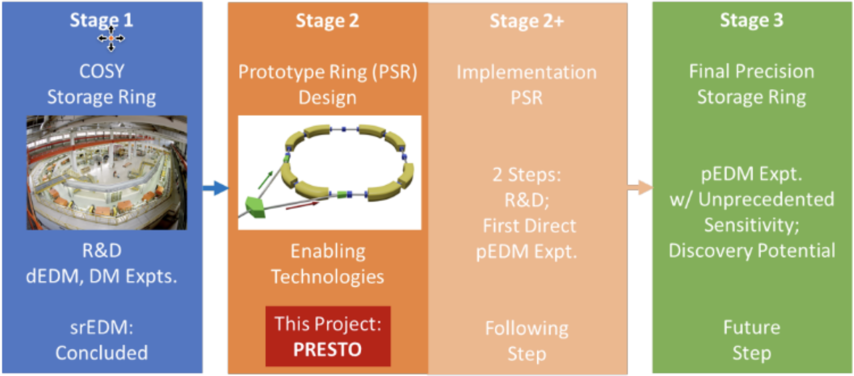
- It includes the result from the JEDI collaboration
  - S. Karanth et al., Phys. Rev. X 13 (2023) 031004

The INCH LoI

Framework: construction of a dedicated SR for EDM studies

Possible approaches

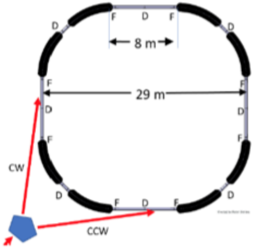
- Staged approach
- One step approach



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

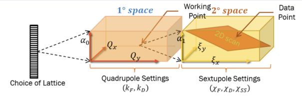
Spares

Optimization of the spin-coherence time in a dedicated ring

Spin-coherence time

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

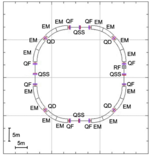
Development of an analytical model

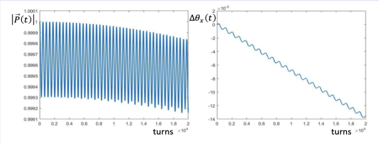


- Minimization of spin-tune difference three 6-pole famlies: $\tau \propto \frac{1}{\Delta\nu_s}$
- $\Delta\nu_s \propto \frac{\Delta L}{L} \equiv$ path lengthening

$$\frac{\Delta L}{L} = -\frac{\pi}{L}(\epsilon_x\xi_x + \epsilon_y\xi_y) + \alpha_0\delta + \alpha_1\delta^2$$
$$= \alpha_1\delta^2 - \frac{\pi}{L}\epsilon_x\xi_x - \frac{\pi}{L}\epsilon_y\xi_y$$

Validation of the model by B-mad simulations



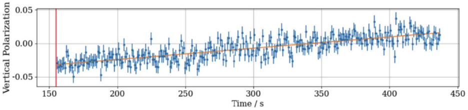


Measurement of EDM resonance strength using pilot bunch
RF Wien filter mapping

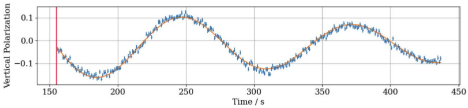
IV major achievement *[Phys. Rev. Research 7, 023257]*

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

- Pilot bunch



- Signal bunch

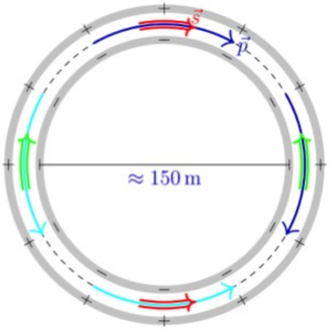


- No oscillations in pilot bunch.
- Decoherence visible in signal bunch.

Stage 3: precision EDM ring

500 m circumference (with E = 8 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)