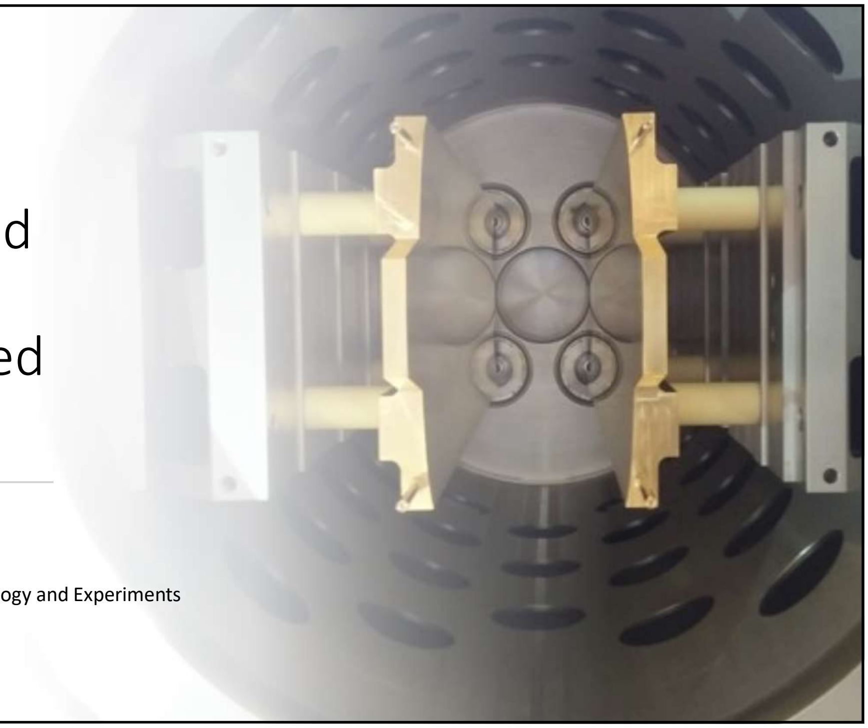
JEDI and beyond – the quest for EDMs of charged particles



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Seminar on Particle Physics, Phenomenology and Experiments
@ Smoluchowski Institute of Physics, JU

7.11.2022

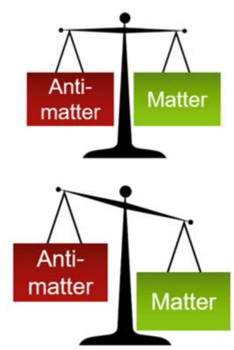
1

EDM - Motivation I: puzzling matter/antimatter asymmetry

- After Big Bang: matter and antimatter balanced
- Currently:

$$\eta = \frac{N_B - N_{\bar{B}}}{N_\gamma} \approx \begin{cases} 10^{-10} & \text{measured} \\ 10^{-18} & \text{from SCM} \end{cases}$$

Bennet et al., Astrophys. J. Suppl. 148 (2003)
Barger et al., PLB 566 (2003)
Bernreuther et al., Lect. Notes Phys. 591 (2002)



- Why?
- CP violation is needed to explain the surplus of matter Sakharov, Soviet Physics Uspekhi 5 (1991)

AW0

2

Slajd 2

AW0 Add reference

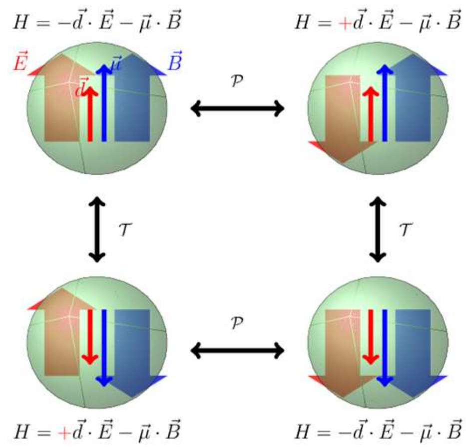
Aleksandra Wrońska, 2022-08-26T10:33:02.514

EDM vs CP violation

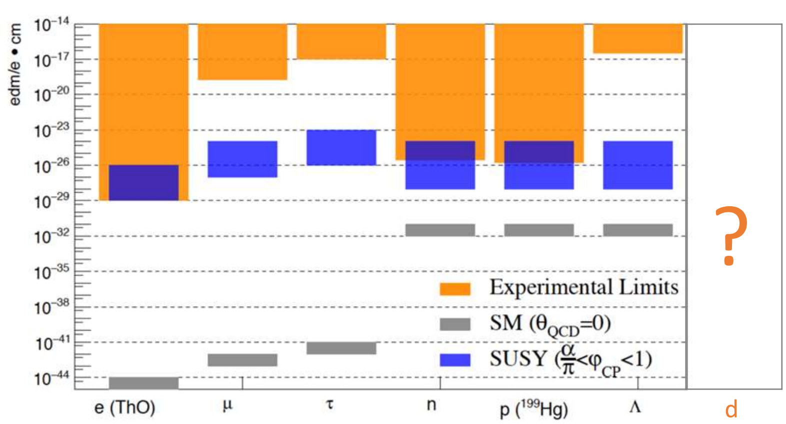
- EDM - fundamental property of elementary particles
$$\vec{d} = d \cdot \vec{s}$$
- Magnetic dipole moment
$$\vec{\mu} = \mu \cdot \vec{s}$$
- Hamiltonian:
$$\hat{\mathcal{H}} = -d \cdot \vec{s} \cdot \vec{E} - \mu \cdot \vec{s} \cdot \vec{B}$$
$$\mathcal{P}(\hat{\mathcal{H}}) = +d \cdot \vec{s} \cdot \vec{E} - \mu \cdot \vec{s} \cdot \vec{B}$$
$$\mathcal{T}(\hat{\mathcal{H}}) = +d \cdot \vec{s} \cdot \vec{E} - \mu \cdot \vec{s} \cdot \vec{B}$$
- According to CPT Theorem:

T Violation = CP Violation

- EDM violates both P and CP symmetry

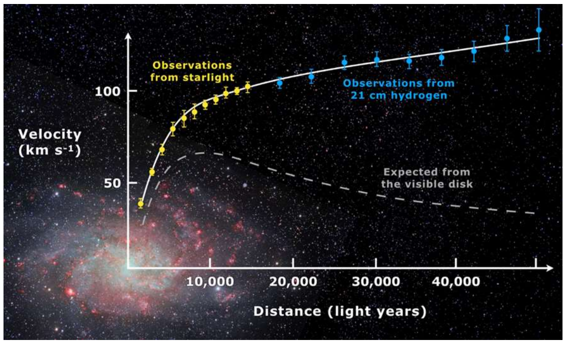


EDM – current knowledge (experiment)



- No direct measurements of **electron**: limit obtained from ThO molecule
- No direct measurements of **proton**: limit obtained from ^{199}Hg
- No measurement at all of deuteron

EDM - Motivation II: nature of dark matter



Rotation curve of galaxy Messier33
M. D. Leo, https : / / en . wikipedia . org / wiki / Galaxy _ rotation _ curve

Only about 1/5 of the universe is made of visible matter.
Large experimental evidence:
- Rotation curves of galaxies
- Gravitational lensing

What is the rest, i.e. Dark Matter made of?
Axions? ALPs?
Physics BSM!

Hunt for ALPs as coherently oscillating waves, inducing oscillating EDMs in SM particles.

Motivation: summary

Baryon Asymmetric Universe
CP violation

→ Static EDM

Dark Matter
BSM particles: axions and ALPs

→ Oscillating EDM

→ Time development of the spin direction of a beam of polarized charged particles in a storage ring. Precisely measured.

Goal: first direct EDM measurement for charged hadrons
Long lifetime
Large particle flux/intensity available
Large E-fields applicable in storage rings
Approach complementary to EDM studies with neutrons

Spin dynamics in a storage ring

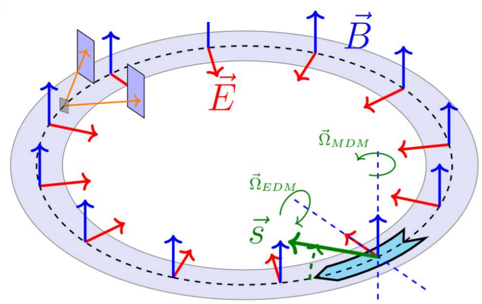
Spin precession of a particle possessing EDM and MDM in the presence of ***E*** and ***B*** field is described by Thomas-BMT equation

Fukuyama et al, Int. J. Mod. Phys A28 (2003)

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

electric dipole moment (EDM): $\vec{d} = \eta\frac{q\hbar}{2mc}\vec{s}$,

magnetic dipole moment (MDM): $\vec{\mu} = 2(G+1)\frac{q\hbar}{2m}\vec{s}$



Dream case: frozen spin: when $\vec{v}||\vec{s}$, only EDM precession, build-up of vertical polarization due to EDM.
Achievable with pure electric field for $G > 0$ particles (proton), when $G = \frac{1}{\gamma^2-1}$.
Otherwise, a smart combination of *E, B* and momentum needed.

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7

The JEDI project

2011 - JEDI collaboration forms at COSY Jülich, Germany

Goals:

1. **Work on prerequisites for EDM search using storage rings**
   - Alignment of ring elements, field stability, homogeneity, shielding
   - Hardware developments
   - Spin tracking
   - Beam intensity at least $\mathbf{N = 4\times10^{10}}$ particles per fill
   - High polarization $\boldsymbol{P = 0.8}$
   - Large electric fields $\boldsymbol{E = 10}$ **MV/m**
   - Long spin conference times $\boldsymbol{\tau\sim}$ **1000 s**
   - Efficient polarimetry with $\boldsymbol{A_y\sim0.6}$ and detection efficiency $\boldsymbol{f\sim0.005}$

2. **perform precursor experiment**
   learn how to keep systematics under control

3. **… search for axions/ALPs**

With these parameters, statistical sensitivity of a 1-year run is
$\sigma_{stat} = \frac{2\hbar}{\sqrt{Nf\tau P}\ {}_yE}$
$= 2.4\times10^{-29}\ e\cdot$cm

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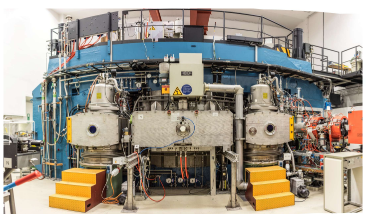
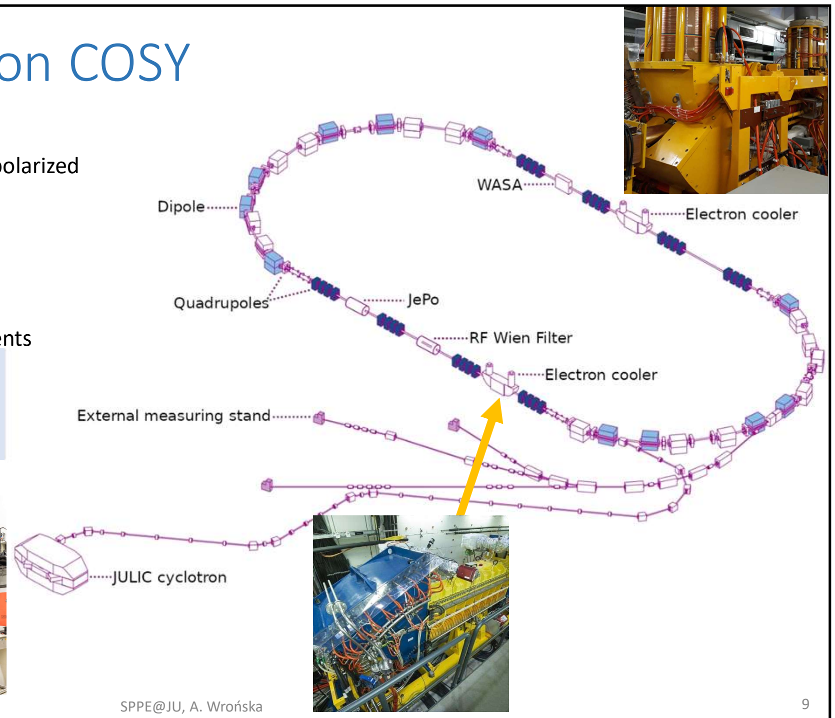
8

Cooler Synchrotron COSY

- Circumference 184 m
- Accelerate and store **polarized** / unpolarized **deuterons** and protons
- $p = 0.3 - 3.7$ GeV/c
- **Internal** and **external** experiments
- 2 **electron** coolers
- 2 **stochastic** coolers
- Hadron physics / **Precision** experiments
- Selected working conditions:
  - Deuteron beam
  - $p = 0.97$ GeV/c, $T = 238$ MeV





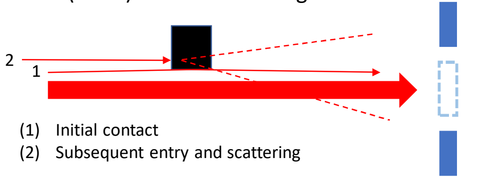
Prerequisites: Polarimetry

- Use forward angle elastic scattering on carbon target.
- White noise beam extraction.
- Spin sensitivity comes from spin-orbit force.
- Proton and deuteron responses are similar.
- Figure of merit shows optimal angle ranges.
- In deuteron case, exclude breakup.

! Sampling favours beam halo.

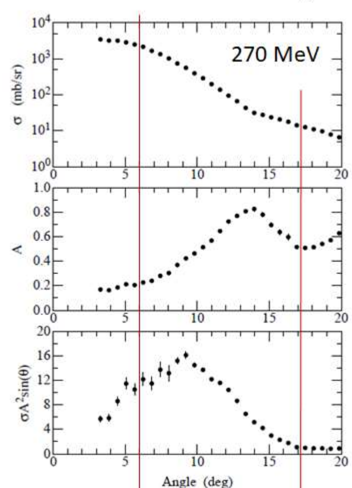
! Beam polarization profile?

Thick (2mm) block carbon target



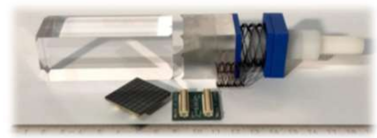
(1) Initial contact
(2) Subsequent entry and scattering

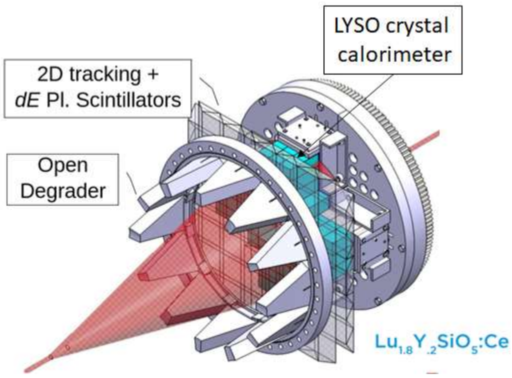
d + ^{12}C elastic scattering

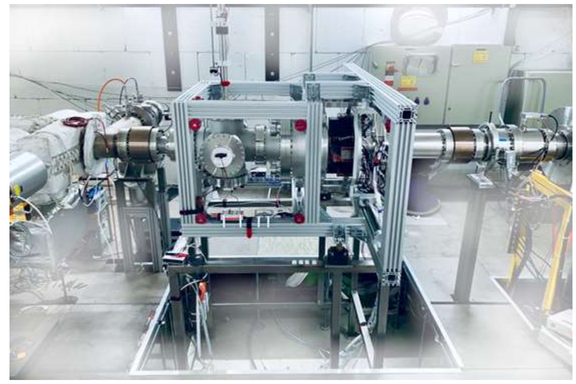


Typical detector range
Average 1.5·A = 0.55

JePo - JEDI Polarimeter



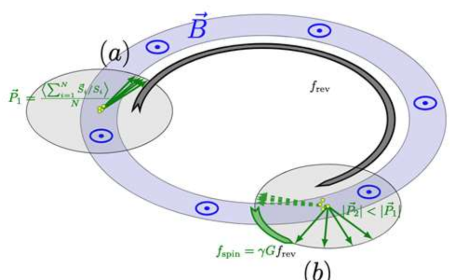




Müller et al, JINST 15 (2020)

JePo has been commissioned and is currently in routine use at JEDI/COSY.
Many initial tests used other existing setups as polarimeters: EDDA and WASA-at-COSY.

Prerequisites: long spin coherence times



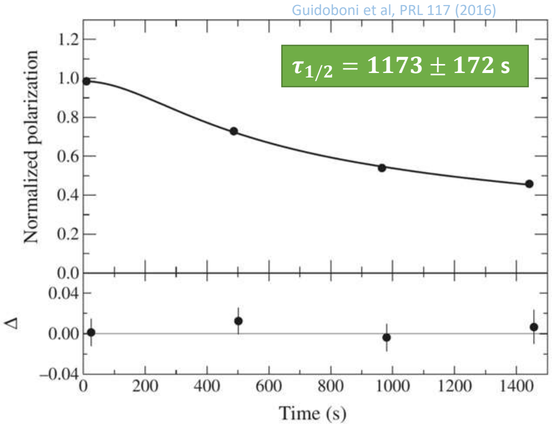
$$\nu_s = \frac{\Omega_{MDM}}{\Omega_{rev}} = \gamma G \approx -0.161 \qquad f_s = 121 \text{ kHz}$$

SCT = complex interplay of:
- Beam emittance
- Momentum spread
- Beam chromaticity
- Orbit deviations

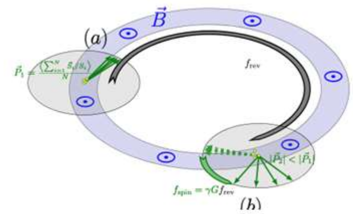
Optimization:
- Beam bunching
- Cooling
- Careful sextupole correction

Measurement of in-plane polarization:
- Events are time-stamped to collect statistics
- Within a time bin (~2 s) , events are distributed into nine angular bins, assuming ν_s
- In-plane polarization ~ to max UD asymmetry amplitude, ν_s is determined thereby too

Bagdasarian et al, Phys Rev AB 17 (2014)
Eversmann et al., PRL 115 (2015)
Guidoboni et al, PRL 117 (2016)



Prerequisites: spin tune control



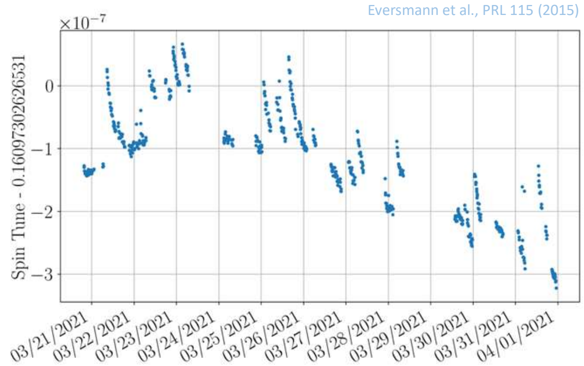
Spin tune crucial for:

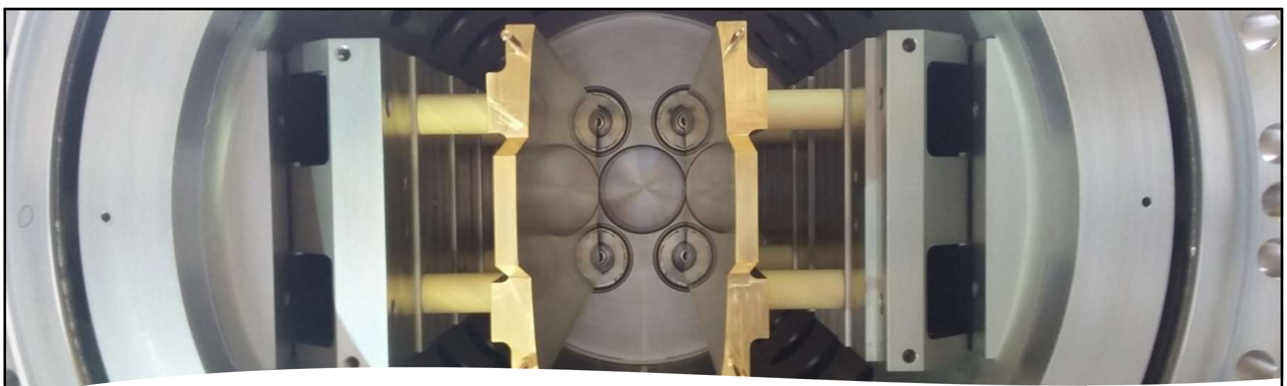
- Analysis of in-plane polarization
- Operation of RF devices
- High precision of determination achieved:

$$\frac{\Delta\nu_s}{\nu_s} \approx 10^{-10}$$

New precision tool to study systematics in a storage ring

Eversmann et al., PRL 115 (2015)





Prerequisites: spin manipulators

- Methods of EDM measurements require tools allowing spin manipulations…
- … without perturbing the beam orbit

Slim et al., NIM A 828 (2016)

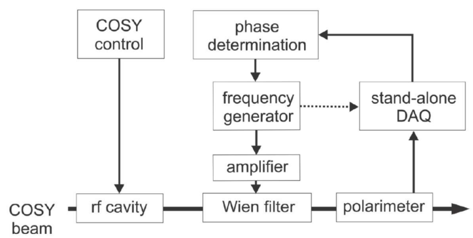
- **RF Wien filter** constructed with Lorentz force $\overrightarrow{F_L} = q(\vec{E} + \vec{v} \times \vec{B}) = 0$
- EDM measurement mode: $\vec{B} = (0, B_y, 0), \vec{E} = (E_x, 0{,}0)$
- If $\boldsymbol{d} \neq \boldsymbol{0}$ $\Longrightarrow$ **accumulation of vertical polarization** over the whole beam cycle duration (given by SCT)

Feedback system

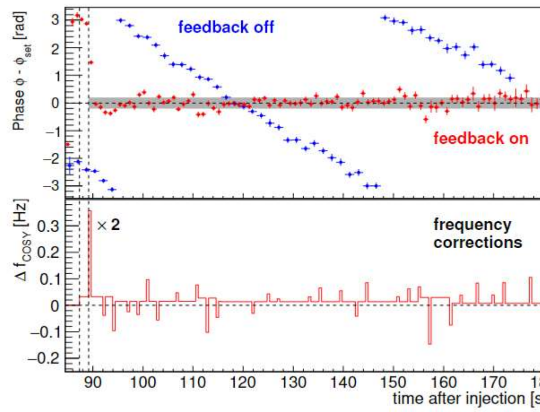
At COSY, frozen spin impossible

Second best – feedback system:

- Maintenance of resonance frequency
- phase-lock between spin precession and ring rf devices



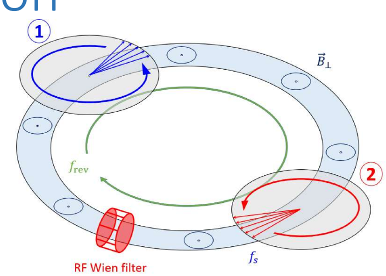
Hempelmann, PRL 119 (2017)



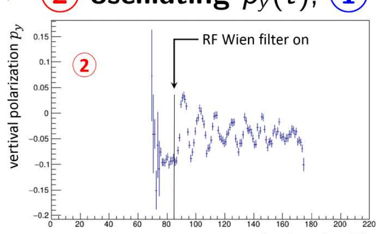
15

Multi-bunch operation Bunch-selective spin manipulation

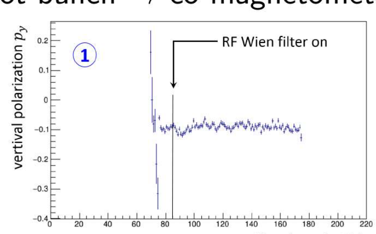
- Two beam bunches present in the ring
- RF Wien filter operated with radial $\vec{B}$ field
- Bunch-selective gating of WF



▸ ② **oscillating** $p_y(t)$, ① **not affected** (pilot bunch → co-magnetometer)



to be submitted soon...

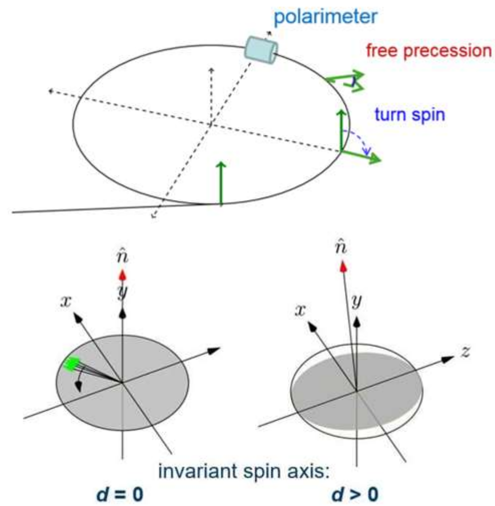


16

First direct measurement of deuteron EDM Precursor experiment

Measurement principle

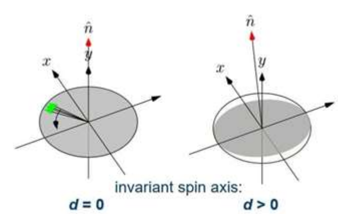
- Measure **influence** of **EDM** on beam **polarization**
- **Injection** of vertically **polarized** beam
- **Rotate** polarization into **accelerator plane** by rf solenoid
- COSY: **magnetic** ring → polarization vector **precesses** about invariant spin axis $\hat{n}$
- d > 0: Tilts $\hat{n}$ in **radial** x direction
- **Goal**: Determination of the **orientation** of $\hat{n}$
- **Problem**: Ring **imperfections** (magnet misalignments,..) lead to rotations of $\hat{n}$ in **radial** (x) and **longitudinal** (z) direction

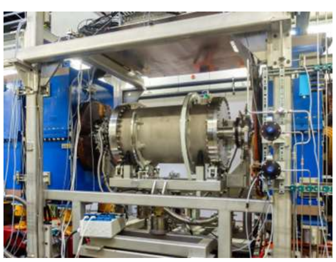


17

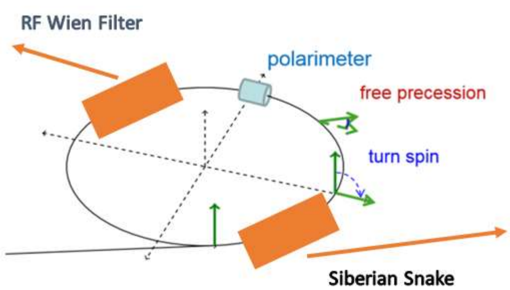
First direct measurement of deuteron EDM Precursor experiment

Measurement principle: determination of $\hat{n}$





- $\vec{E} \perp \vec{B} \perp \vec{v} \rightarrow \vec{F_L} = 0$
- $\vec{B}$ - field kicks $\hat{n}$ in **radial** direction (x) at WF
- **Rotational** device φ^{WF}



- Longitudinal $\vec{B}$ field
- $\vec{B}$ - Field kicks $\hat{n}$ in **longitudinal** direction (z) by ξ^{Sol}

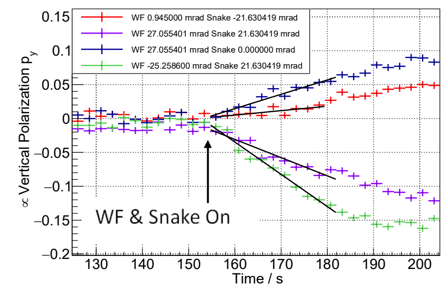
18

First direct measurement of deuteron EDM Precursor experiment

Measurement principle: mapping resonance strength

- Fix Wien Filter φ^{WF} and Siberian Snake (Solenoid) ξ^{Sol} rotation angles
- Measure **slope** of linear increasing vertical polarisation **after** turning on Wien Filter and Siberian Snake
- **Repeat** for different settings for **Wien Filter** and **Siberian Snake**
- **Resonance** strength is given by

$$\epsilon(\phi^{WF}, \xi^{Sol}) = \frac{\Omega^{p_y}}{\Omega^{rev}} \sim |\dot{p_y}|$$



19

First direct measurement of deuteron EDM Precursor experiment

Preliminary results

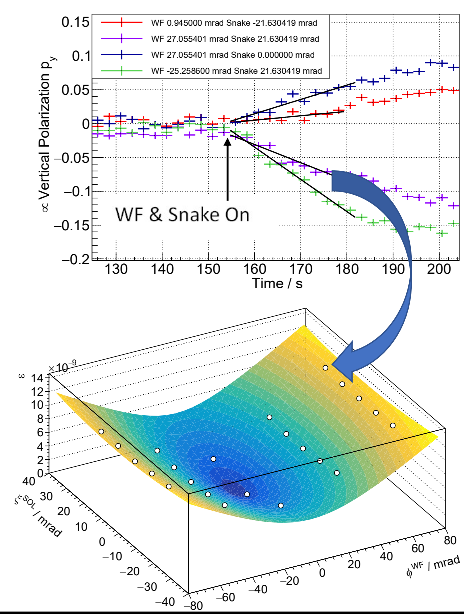
$$\epsilon(\phi^{WF}, \xi^{Sol}) = \left[A_{WF}^2 \left(\phi^{WF} - \phi_0^{WF}\right)^2 + \frac{A_{Sol}^2}{4\sin^2(\pi\nu_s)} \left(\xi_0^{Sol} - \xi^{Sol}\right)^2 \right]^{\frac{1}{2}}$$

Rathmann et al, Phys Rev AB 23 (2020)

Orientation of $\hat{n}$ including ring **imperfections** and **EDM** signal is:

$$\phi_0^{WF} = -2.91(8)\ \text{mrad}$$
$$\xi_0^{SOL} = -5.22(7)\ \text{mrad}$$

1. **Minimum** represents invariant spin axis orientation **including** EDM and ring imperfections
2. **Simulated** spin tracking shall determine orientation of stable spin axis **without** EDM
3. **EDM** is determined from difference of 1) and 2)



Work in progress…

20

Axion/ALP hunting

Measurement principle

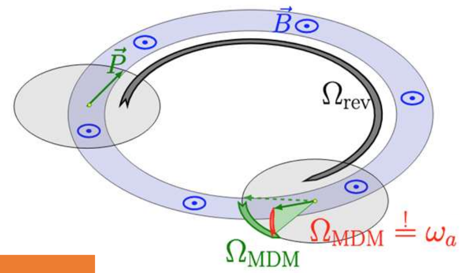
- Axions and ALPs:
  - Solution of strong CP problem (PQ symmetry)
  - Dark Matter candidate
- **Oscillating** EDM *d* induced in hadrons via axion-gluon coupling
- Oscillation frequency related to axion **mass**

$$d = d_{DC} + d_{AC}\sin(\omega_a t + \varphi_a)$$

$$\omega_a = \frac{m_a c^2}{\hbar}$$

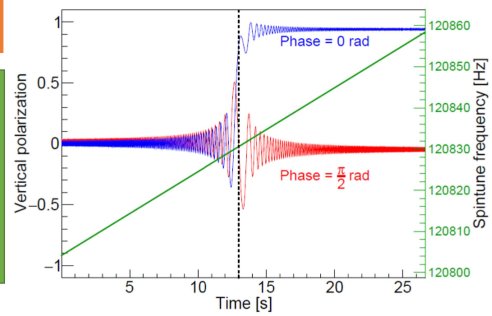
- Vertical polarization **jump** if

$$\Omega_{MDM} = \gamma G \Omega_{rev} \stackrel{!}{=} \omega_a$$



But:
- What s the axion/ALP mass?
- What is the phase?

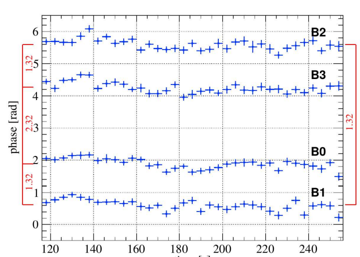
Solution:
- Ramp the beam momentum, scanning certain mass range
- Run with 4 beam bunches, with different phases



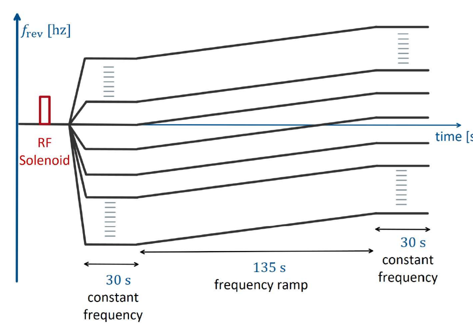
Axion/ALP hunting

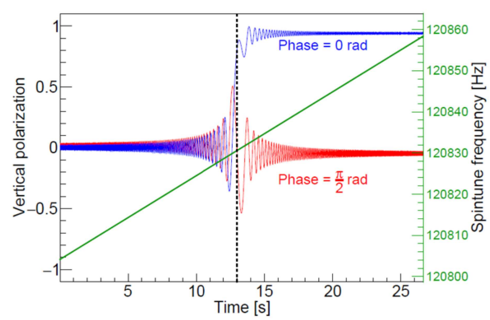
Experiment

- Momentum scan
  - = Ω_{MDM} scan
  - = axion/ALP mass scan
- 4 beam bunches



- Scanned frequency range: 120.05 – 121.45 kHz
- Covered axion/ALP mass range: (4.96 – 5.02) 10^{-10} eV
- In each time bin, search for vertical polarization jump



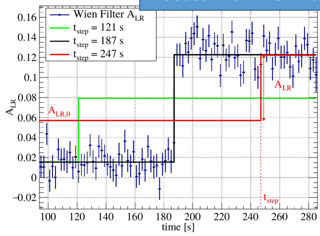


$$\Omega_{MDM} = \gamma G \Omega_{rev} \stackrel{!}{=} \omega_a$$

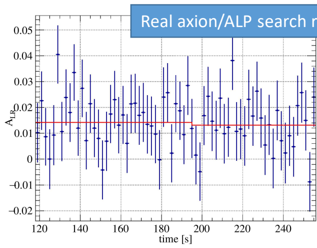
Axion/ALP hunting

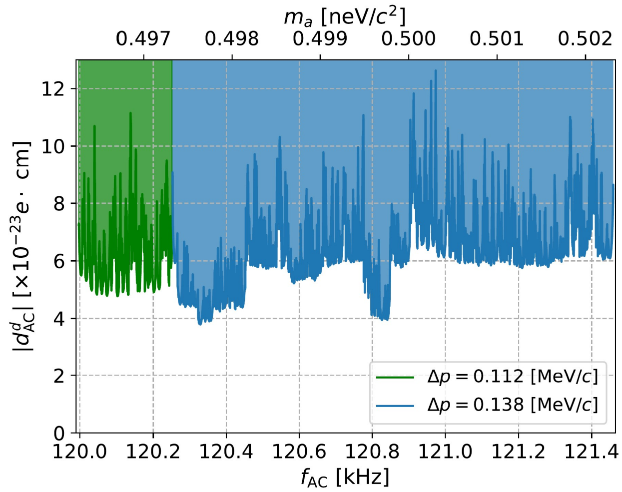
Results

Calibration run, fake axion signal induced with Wien filter



Real axion/ALP search run



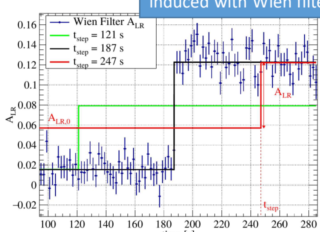


- No axion/ALP signal observed
- Upper limits on d_{AC} in the scanned mass range determined
- Sensitivity $\sim 10^{-2}$ $e \cdot$ cm after only 4 weeks of beam time (and only ~3 days of actual data taking!)
- **Consequences for various ALP couplings + further details in** **Karanth et al, arXiv:2208.07293 [hep-ex]**

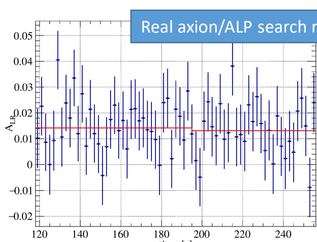
Axion/ALP hunting

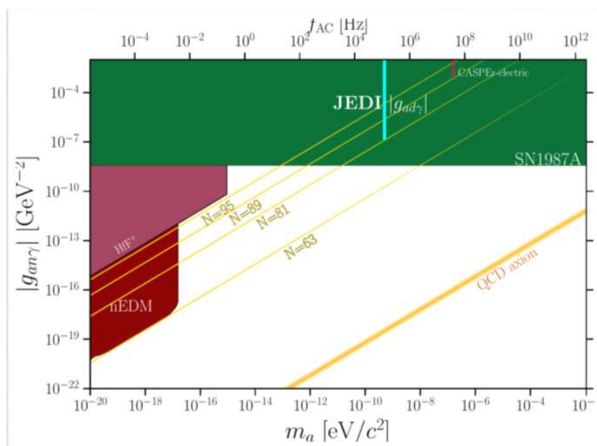
Results

Calibration run, fake axion signal induced with Wien filter



Real axion/ALP search run





- No axion/ALP signal observed
- Upper limits on d_{AC} in the scanned mass range determined
- Sensitivity $\sim 10^{-23} e \cdot$ cm after only 4 weeks of beam time (and only ~3 days of actual data taking!)
- **Consequences for various ALP couplings + further details in** **Karanth et al, arXiv:2208.07293 [hep-ex]**

Next steps in the quest

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

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}

1
Precursor Experiment
dEDM proof-of-capability
(orbit and polarization control;
first dEDM measurement)

Mission at COSY accomplished (almost)

- Magnetic storage ring
- Many useful techniques of spin manipulation and polarization measurement developed/mastered
- Devoted community of experts formed
- First direct measurement of deuteron EDM performed, results coming soon
- Proof-of-principle experiment for the storge-ring based method of ALP search
- However, we need more sensitivity to find the answers…

7.11.2022 SPPE@JU, A. Wrońska 25

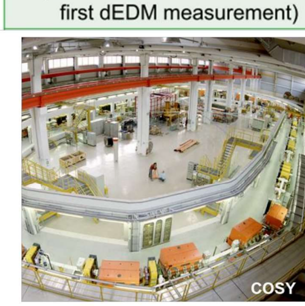
25

Next steps in the quest

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

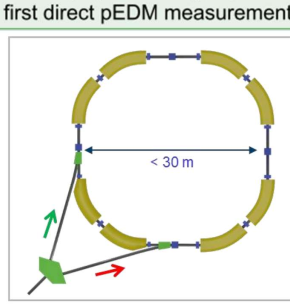
10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21} 10^{-22} 10^{-23} 10^{-24} 10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29}

1
Precursor Experiment
dEDM proof-of-capability
(orbit and polarization control;
first dEDM measurement)



PRESTO

2
Prototype Ring
pEDM proof-of-principle
(key technologies,
first direct pEDM measurement)



Prototype ring

- Electrostatic/magnetic elements
- Frozen spin (*e, p, d,* He-3) for higher sensitivity
- Dual beam (CW/CCW) for better control of systematics
- Gain experience in building precision rings,
- Find limitations and mitigate them

- Even broader community proposed a project *PRESTO* within HORIZON-INFRA-2022 to prepare a CDR for such a ring

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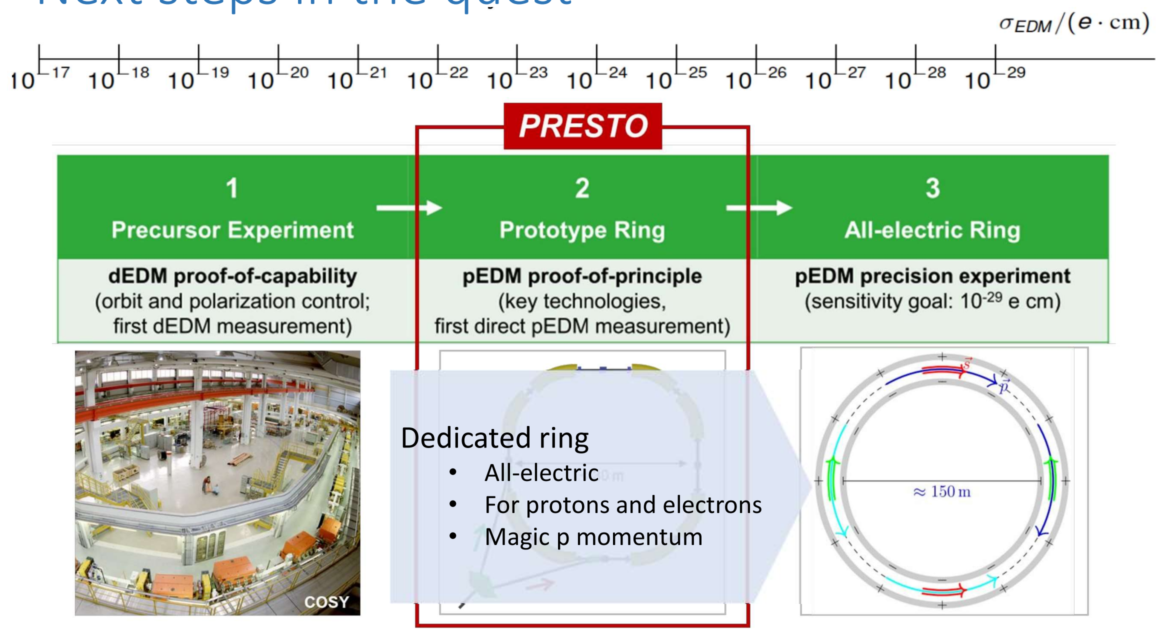
26

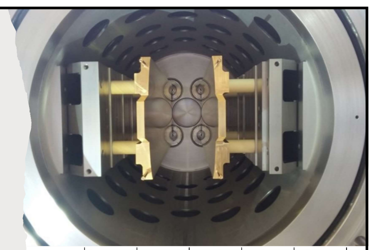
Next steps in the quest

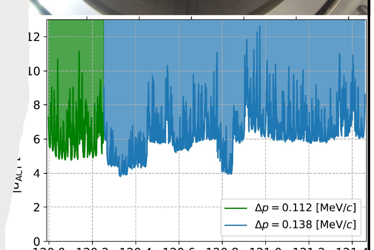


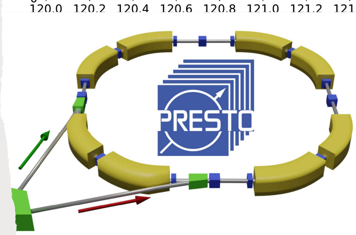
27

Summary

- EDMs are a potential
  - Source of CP violation
  - Tool to search for DM particles
- The JEDI collaboration
  - Toolbox for experimental precision spin physics with storage rings
  - Preparation to observe EDM effect on beam polarization
  - The first direct measurement of deuteron EDM
  - Demonstration of a method to look for axions/ALPs using a storage ring
- Future: consensus about a staged approach
  - An E/B prototype ring (*e, p, d,* He-3), sensitivity $\sim 10^{-24}\ e \cdot \mathrm{cm}$
  - A full glory, all-electric proton ring, sensitivity $\sim 10^{-29}\ e \cdot \mathrm{cm}$







28