SEARCH FOR THE ELECTRIC DIPOLE MOMENT OF CHARGED PARTICLES USING STORAGE RINGS

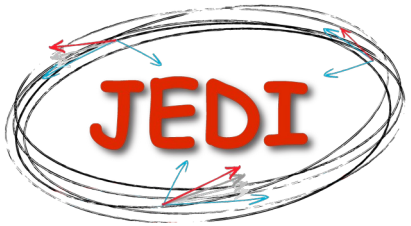
VERA SHMAKOVA

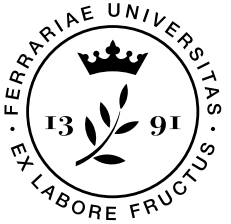
ON BEHALF OF THE JEDI COLLABORATION

EUROPEAN NUCLEAR PHYSICS CONFERENCE 2022

SANTIAGO DE COMPOSTELA

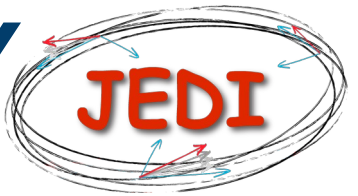
25.10.2022





Università degli Studi di Ferrara

MATTER-ANTIMATTER ASYMMETRY



- Why Universe Matter dominated?

• Experiment: *V. Barger, et al, Phys.Lett.B566, 8 (2003)*	$\frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$
• Expectation from SCM: *W. Bernreuther, Lect. Notes Phys.591, 237 (2002)*	$\frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-18}$

- Preference of matter (A. Sakharov criteria, 1967)

_CP_ violation

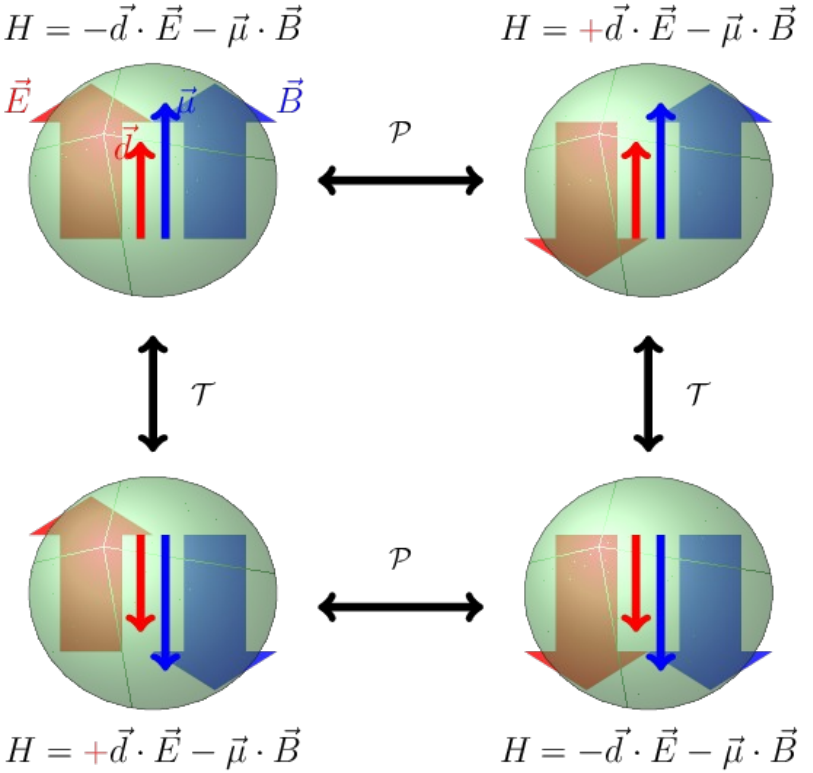
- *CP* violation in SM is not sufficient

ELECTRIC DIPOLE MOMENT

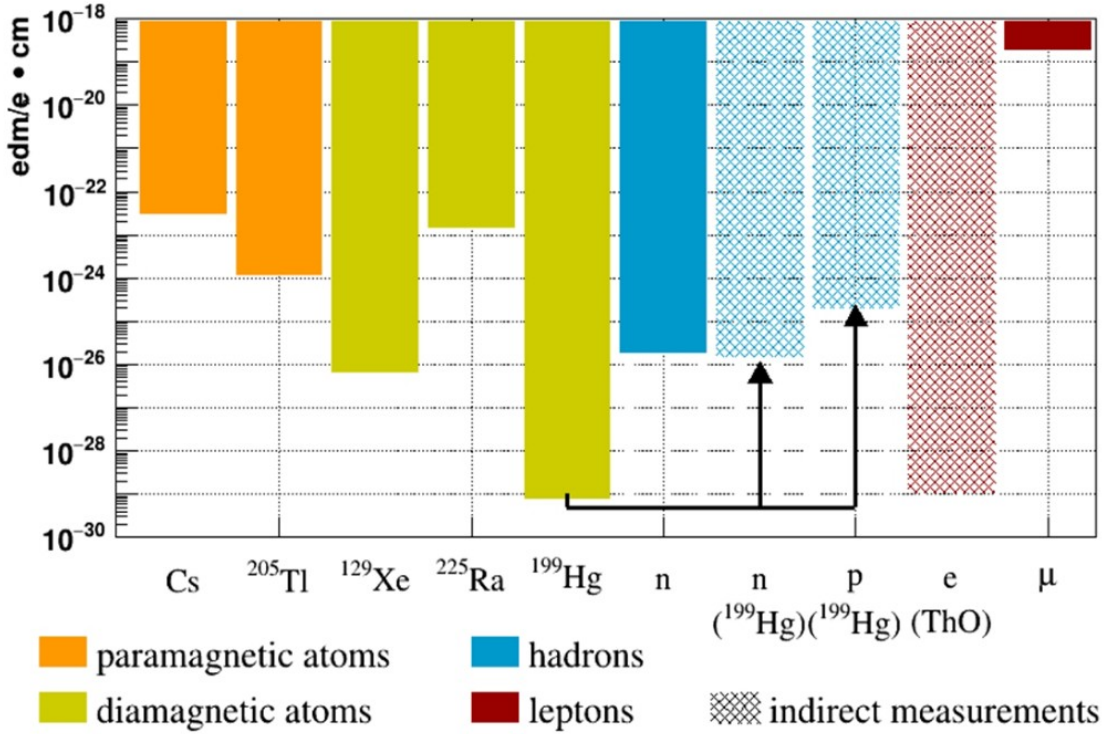
- EDM violates both T, P symmetries

- EDM violates CP symmetry (if CPT conserved)

- EDM may possibly contain the missing cornerstone to explain the matter-antimatter asymmetry



EXISTING LIMITS ON EDM



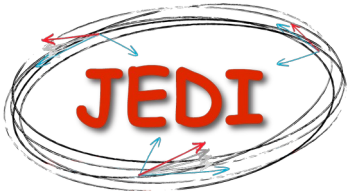
* F. Abusaif et al., "Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study," CERN Yellow Report **257** (2021), **https://doi.org/10.23731/CYRM-2021-003**

No direct measurements of electon EDM ➡ limit from ThO molecule

No direct measurements of proton EDM ➡ limit from $^{199}_{80}\mathrm{Hg}$

No measurement of deuteron EDM

EDM AT STORAGE RINGS



THOMAS - BMT EQUATION

$$\frac{d\vec{S}}{dt} = [\vec{\Omega}_{MDM} - \vec{\Omega}_{cycl} + \vec{\Omega}_{EDM}] \times \vec{S}$$

$$\vec{\Omega}_{MDM} - \vec{\Omega}_{cycl} = -\frac{q}{m}\{G\vec{B} - (G - \frac{1}{\gamma^2 - 1})\frac{\vec{\beta} \times \vec{E}}{c}\}$$

$$\vec{\Omega}_{EDM} = -\frac{\eta q}{2mc}\{\vec{E} + c\vec{\beta} \times \vec{B}\}$$

EDM AT STORAGE RINGS

THOMAS - BMT EQUATION

$$\frac{d\vec{S}}{dt} = [\vec{\Omega}_{MDM} - \vec{\Omega}_{cycl} + \vec{\Omega}_{EDM}] \times \vec{S}$$

$$\vec{\Omega}_{MDM} - \vec{\Omega}_{cycl} = -\frac{q}{m}\{G\vec{B} - (G - \frac{1}{\gamma^2 - 1})\frac{\vec{\beta} \times \vec{E}}{c}\} \quad \Rightarrow \quad \vec{\Omega}_{EDM} = -\frac{\eta q}{2mc}\{\vec{E} + c\vec{\beta} \times \vec{B}\}$$

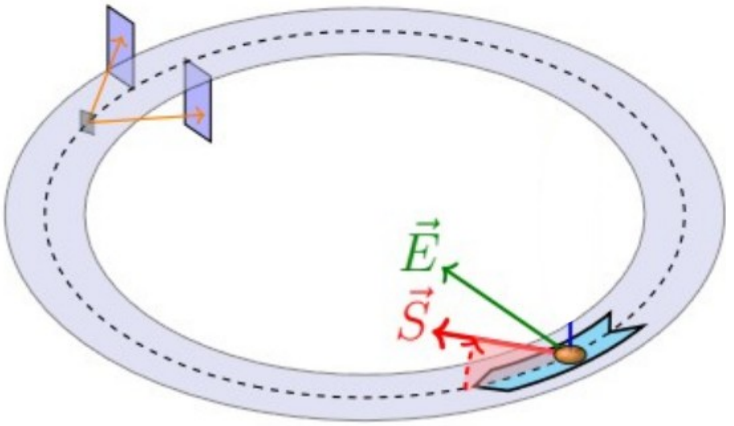
$\vec{B} = 0$; $(G - \frac{1}{\gamma^2 - 1}) = 0$

"Frozen spin": in the absence of EDM spin stay aligned to momentum

In case of purely electric ring:

- magnetic field is absent
- momentum is chosen that term $(G - \frac{1}{\gamma^2 - 1}) = 0$

⇒ radial electric field causes the spin to precess out of the plane linearly



EDM FOR CHARGED PARTICLE IN 3 STAGES

PRESTO

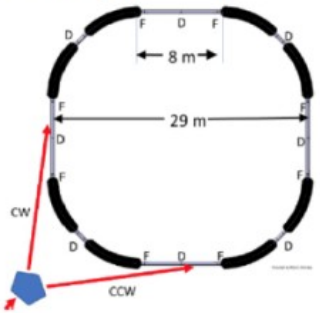
Stage 1

- precursor experiment

pure magnetic ring

Stage 2

- prototype ring



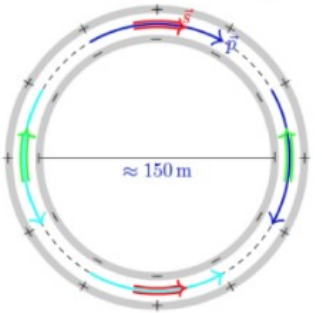
combined E/B ring

simultaneous CW-CCW beams

frozen spin

Stage 3

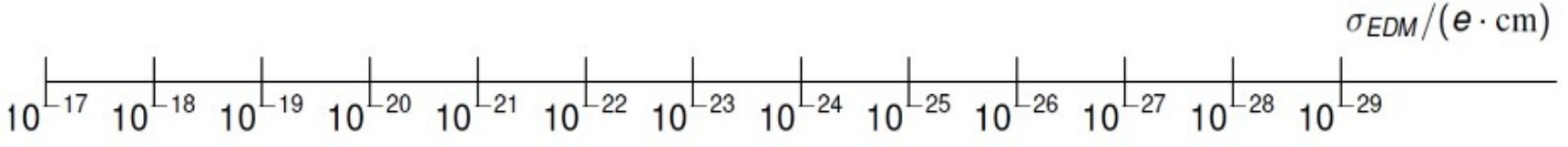
- dedicated storage ring



all electric proton ring

simultaneous CW-CCW beams

frozen spin

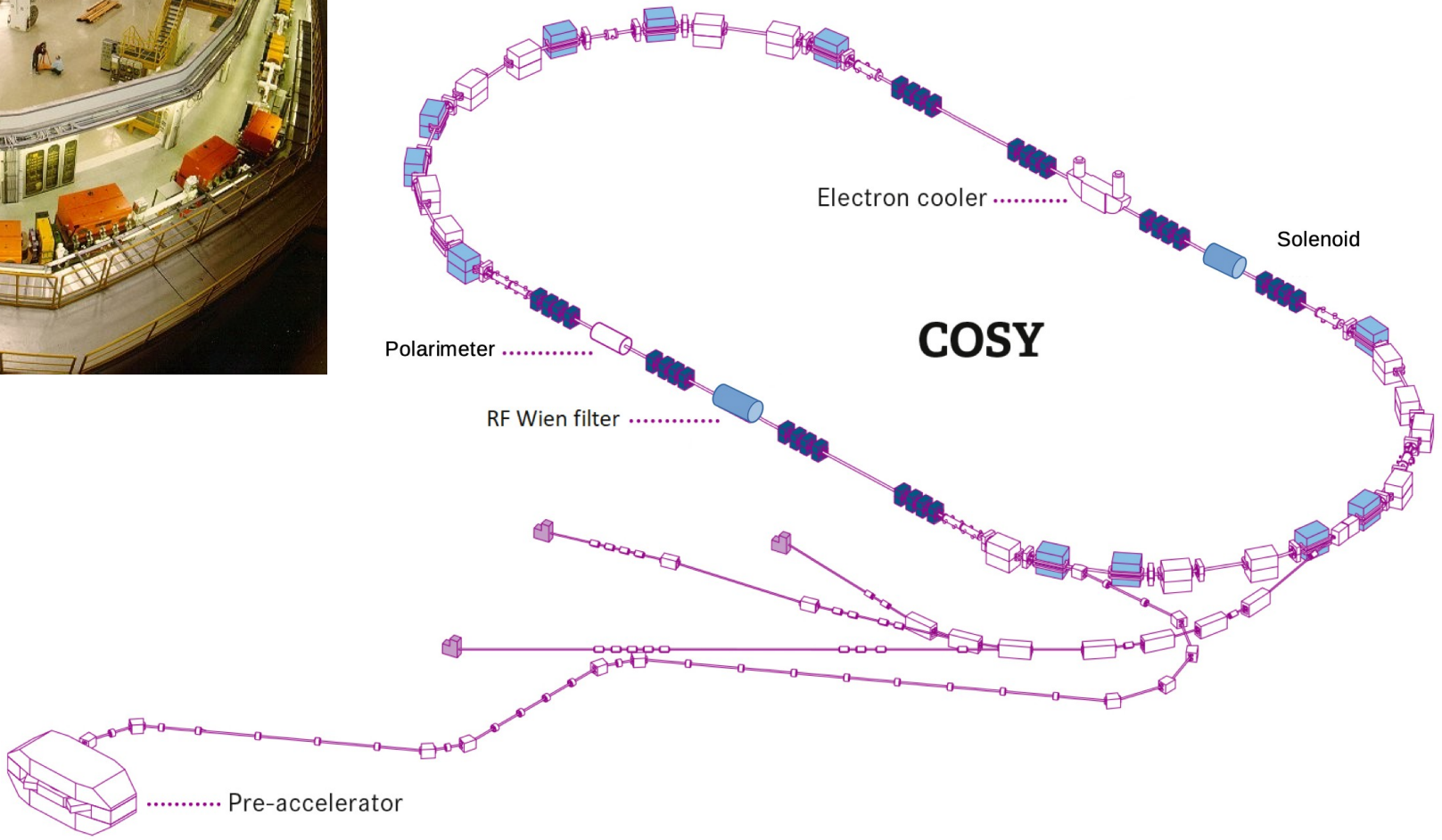


* F. Abusaif et al., “Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study,” 2019
https://arxiv.org/abs/1912.07881

PRECURSOR EXPERIMENT AT COSY

COoler SYnchrotron COSY:

- magnetic storage ring
- polarized protons and deuterons
- momenta p = 0.3 – 3.7 GeV/c
- starting point for EDM measurement



EDM AT MAGNETIC RING

THOMAS - BMT EQUATION

$$\frac{d\vec{S}}{dt} = [\vec{\Omega}_{MDM} - \vec{\Omega}_{cycl} + \vec{\Omega}_{EDM}] \times \vec{S}$$

$$\vec{\Omega}_{MDM} - \vec{\Omega}_{cycl} = -\frac{q}{m}\{G\vec{B} - (G - \frac{1}{\gamma^2 - 1})\frac{\vec{\beta} \times \vec{E}}{c}\}$$

$$\vec{\Omega}_{EDM} = -\frac{\eta q}{2mc}\{\vec{E} + c\,\vec{\beta} \times \vec{B}\}$$

MDM causes fast spin precession in horizontal plane

In **pure magnetic ring** motional electric field term $(c\,\vec{\beta} \times \vec{B})$

access to EDM

RF WIEN FILTER

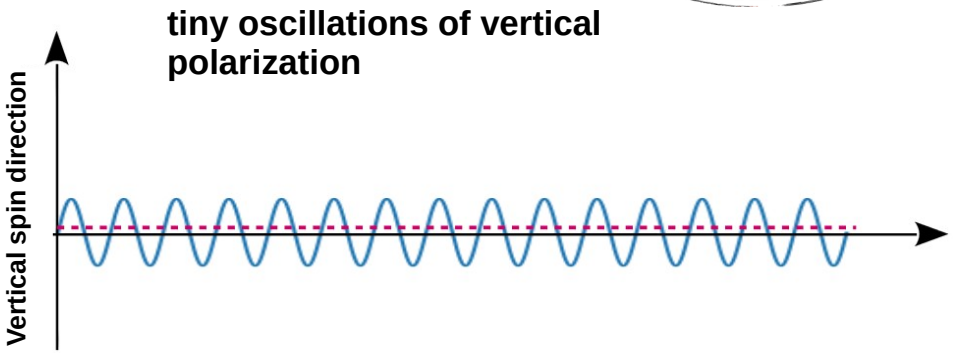
In the magnetic ring

momentum ↑↑ spin ⇨ spin kicked up by EDM

momentum ↑↓ spin ⇨ spin kicked down by EDM

⇩

no accumulation of vertical asymmetry



RF WIEN FILTER

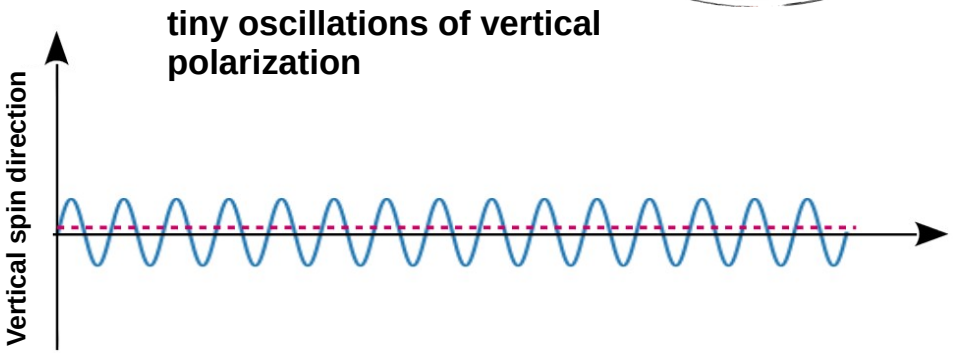
In the magnetic ring

momentum ↑↑ spin ⇨ spin kicked up by EDM

momentum ↑↓ spin ⇨ spin kicked down by EDM

⇩

no accumulation of vertical asymmetry

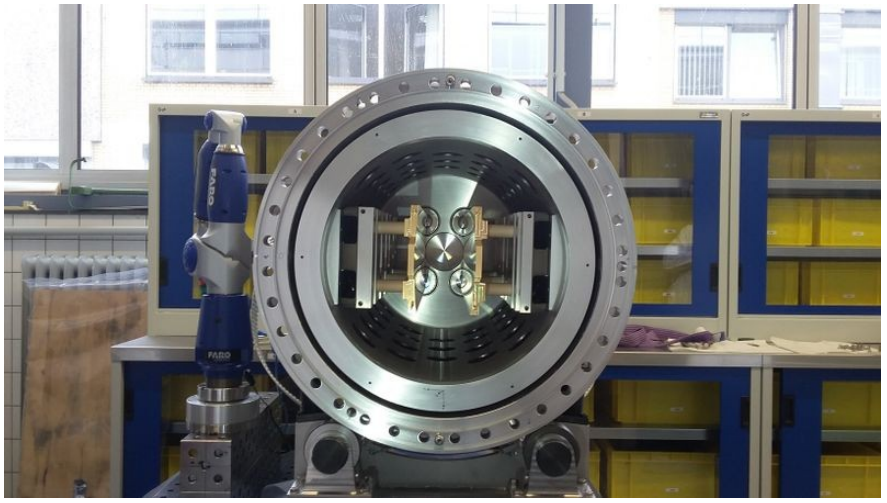


RF Wien filter

*Heberling, Hölscher and **J. Slim***

J. Slim et al. Nucl. Instrum. Methods Phys. Res. A 828, 116 (2016)

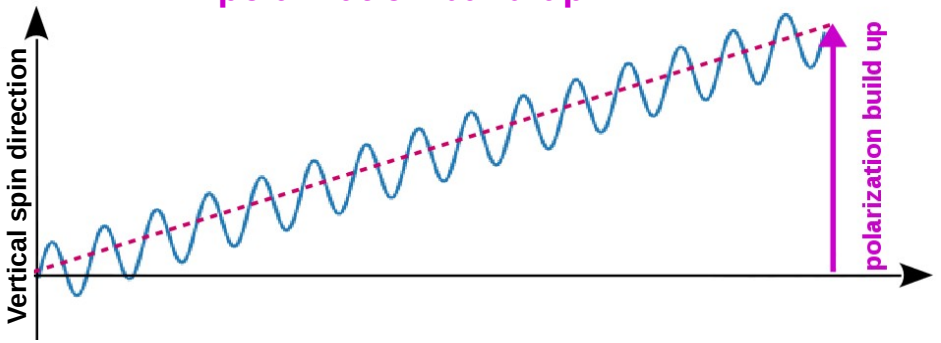
- Lorentz force $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0$
- $\vec{B} = (0, B_y, 0)$ and $\vec{E} = (E_x, 0, 0)$



phase lock between spin precession and RF Wien filter

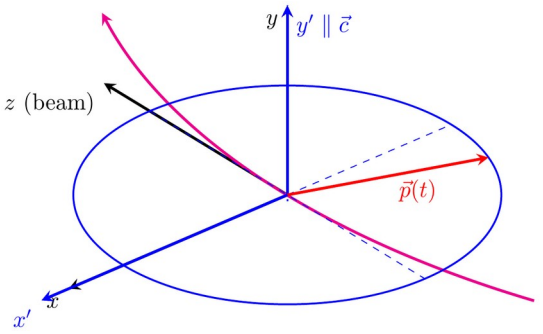
⇩

polarization build-up

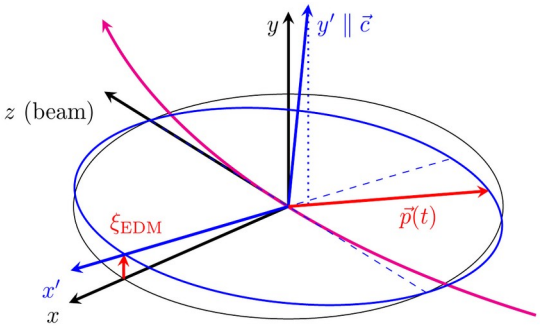


EFFECT ON INVARIANT SPIN AXIS

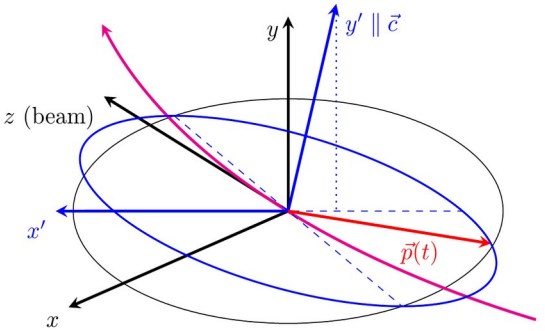
EDM absent



Pure EDM effect

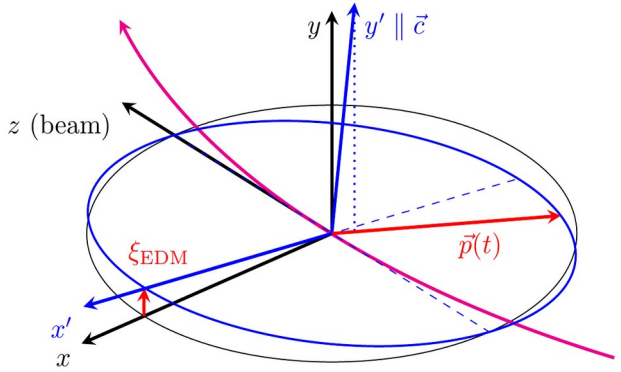


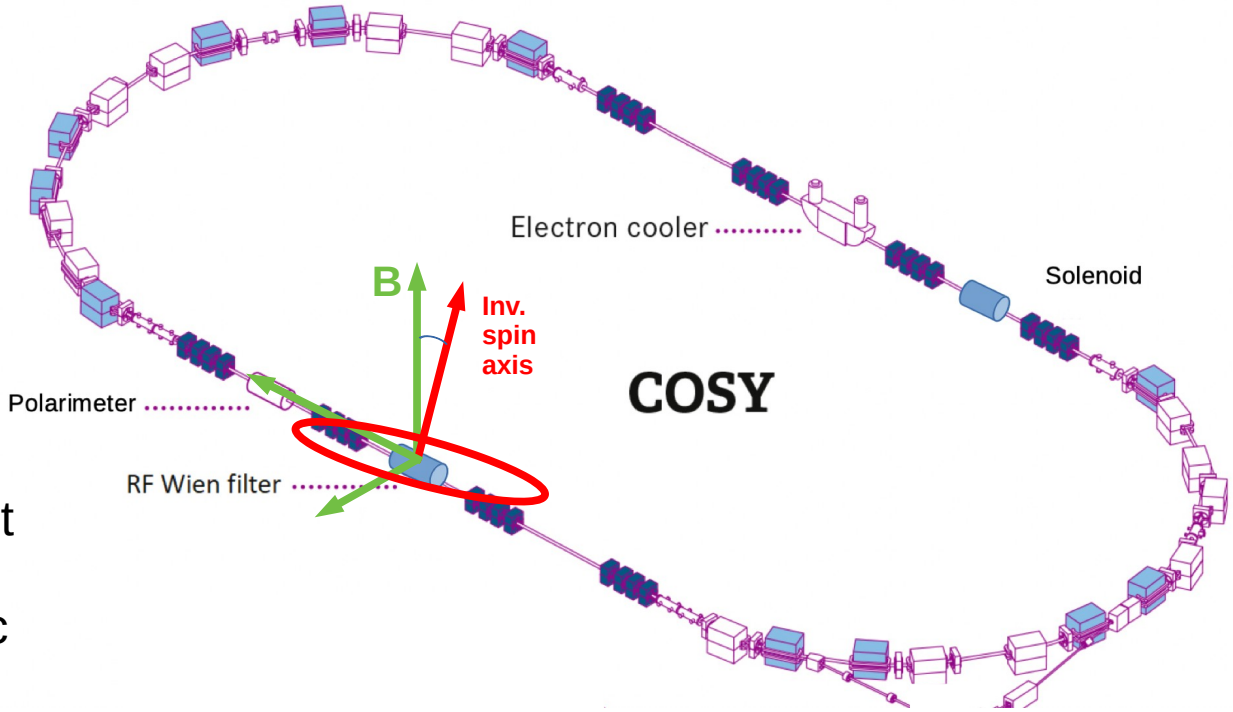
EDM + magnetic misalignments



MEASUREMENT OF THE EDM EFFECT

How the EDM effect actually measured:

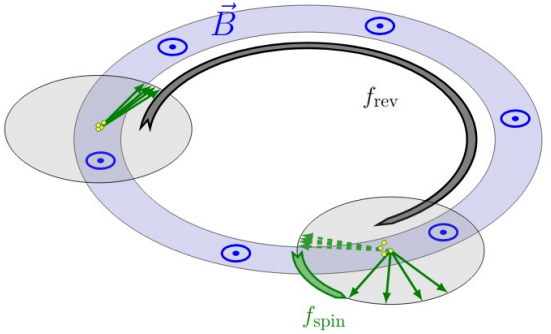




- The RF Wien filter is rotated about beam axis:
  - it generates radial magnetic field, which allows to compensate to radial tilt of invariant spin axis
- Solenoid introduces longitudinal magnetic field:
  - It change the invariant spin axis direction longitudinally

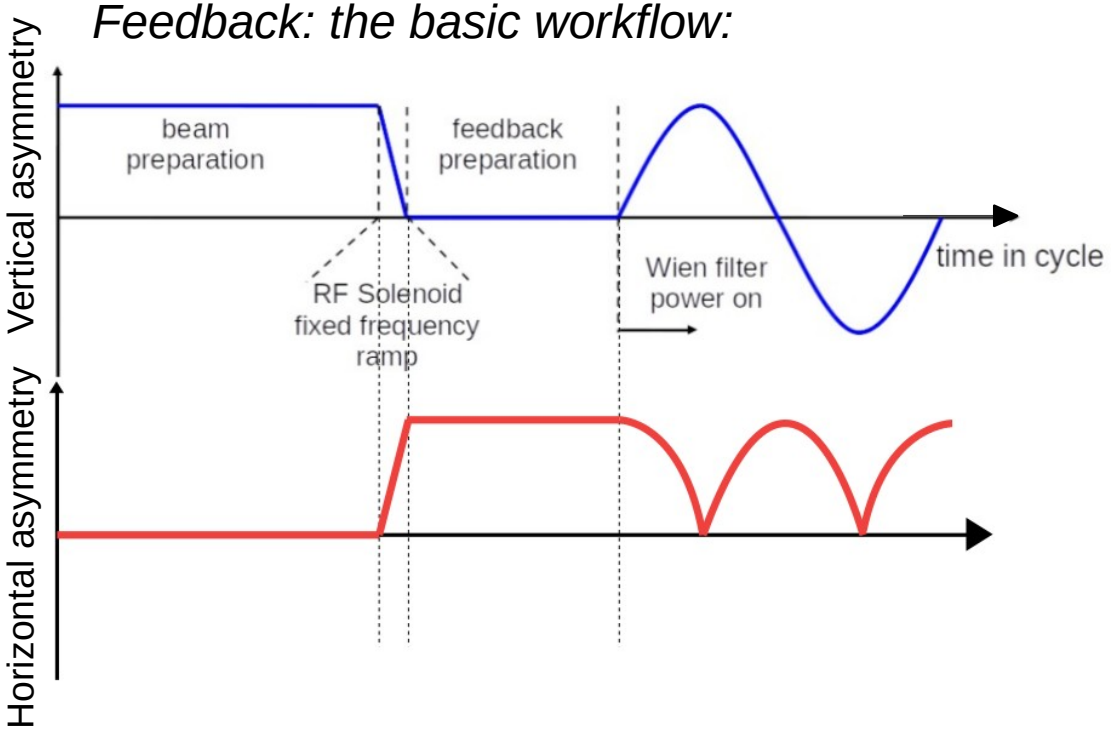
PRINCIPLE OF MEASUREMENTS

- Coherent ensembles in ring plane ➡ spin coherence time has to be longer than a measurement
- SCT > 1000 s.



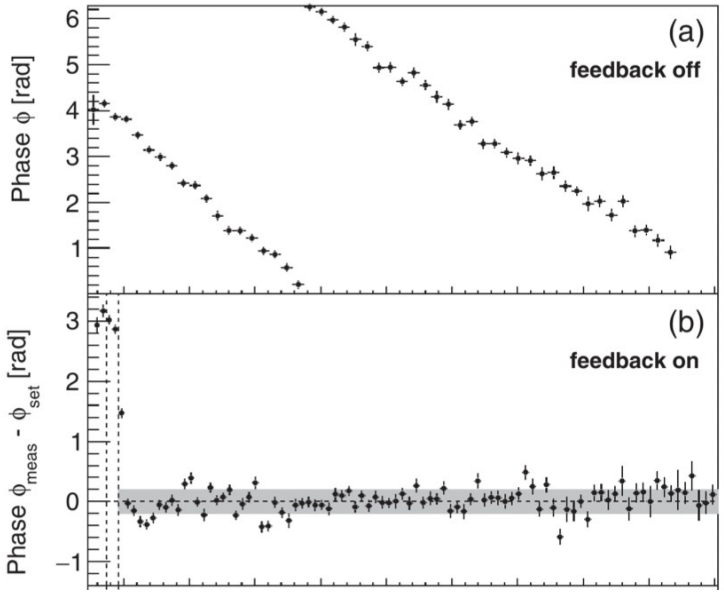
- Spin precesses with 120 kHz.
- Wien filter operates on resonance:
  $f = f_{COSY} + f_{spin\ pres} = 871.430$ kHz
- Phase lock between spin precession and Wien filter

Feedback: the basic workflow:

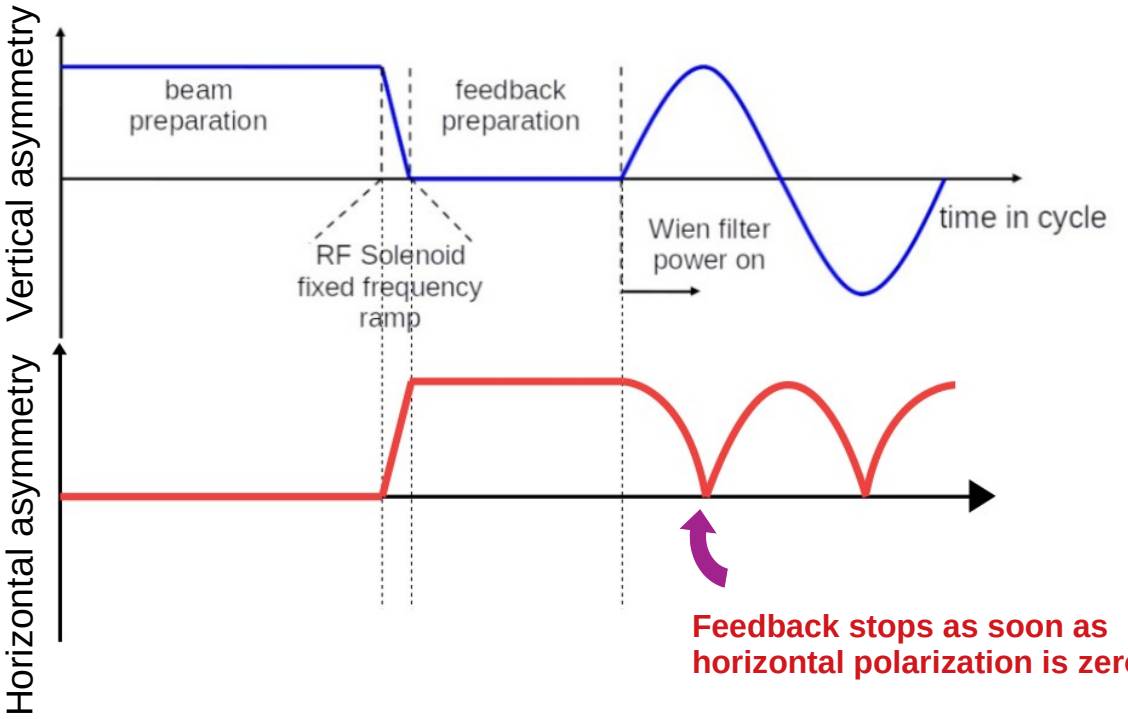


PRINCIPLE OF MEASUREMENTS

- Feedback monitors spin precession phase and adjust WF frequency to maintain the relative phase between spin precession and Wien filter
- Adjustment uncertainty of 0.2 rad



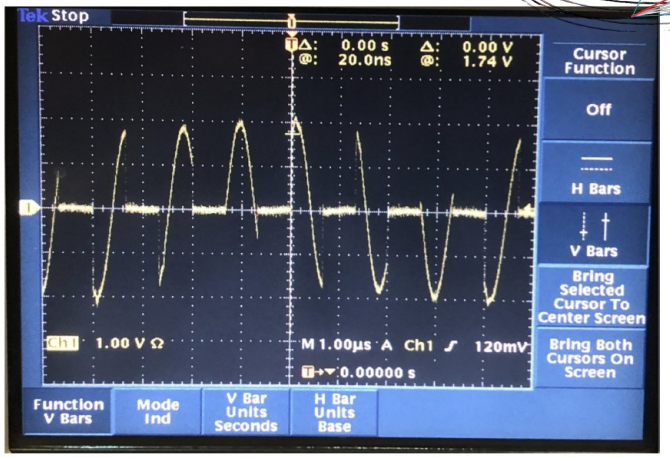
Feedback: the basic workflow



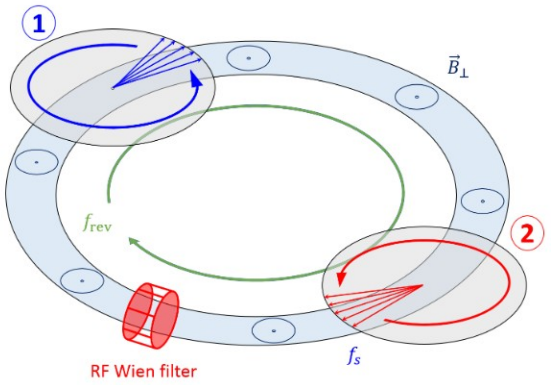
Feedback stops as soon as horizontal polarization is zero

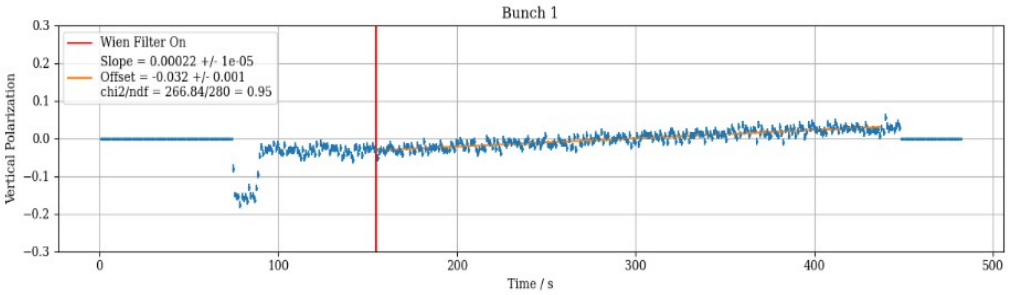
PRINCIPLE OF MEASUREMENTS

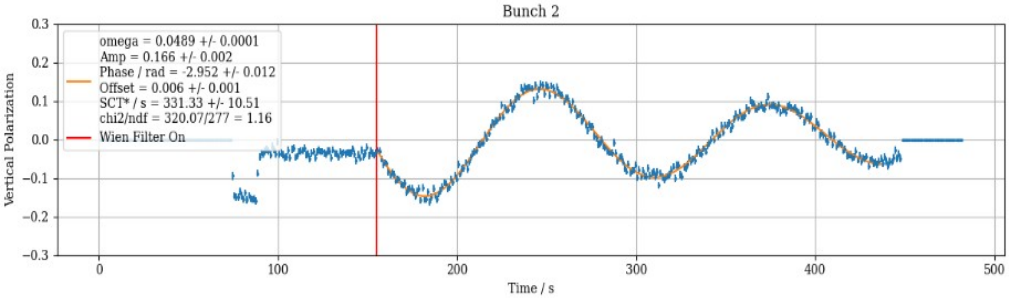
- Method to manipulate the spin of one bunch out of several in the ring
- 8 high-speed RF switches to gate the WF power for one of two bunches
- Capable of short switch time ~ few ns



- Bunch ② feels the power and oscillate
- Bunch ① is used as pilot bunch
- for phase locking







RESULTS

Parametric resonance strength defined as:

$$\varepsilon^{EDM} = \frac{\Omega^{P_y}}{\Omega^{rev}}$$

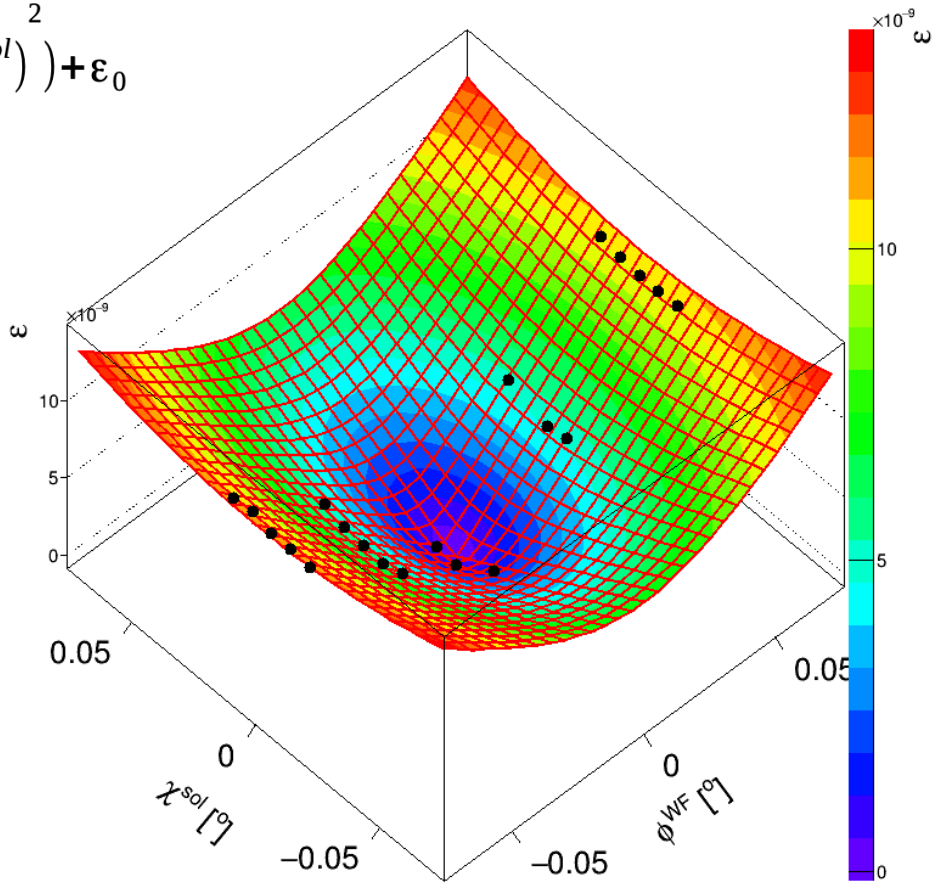
$$\varepsilon = \frac{\chi_{WF}}{4\pi}\sqrt{\left(A_{WF}^2\left(\phi_0^{WF}-\phi^{WF}\right)^2 + A_{Sol}^2\left(\frac{\chi_0^{sol}}{2\sin\left(\pi\nu_s\right)}-\chi^{sol}\right)^2\right)} + \varepsilon_0$$

Minimum of the surface shows orientation of invariant spin axis:

φ_0^{wf} = 2.42 +- 0.04 mrad

X_0^{sol} = -3.96 +- 0.04 mrad

Orientation of precession axis without EDM will come out of spin tracking calculations



AXION / AXION LIKE PARTICLES (APL)

- First experiment for axion/ALP search at storage ring
- Oscillating EDM induced in hadrons via axion-gluon coupling
- Solve strong CP problem
- Axions and ALPs are the dark matter candidates
- Oscillating frequency related to axion mass

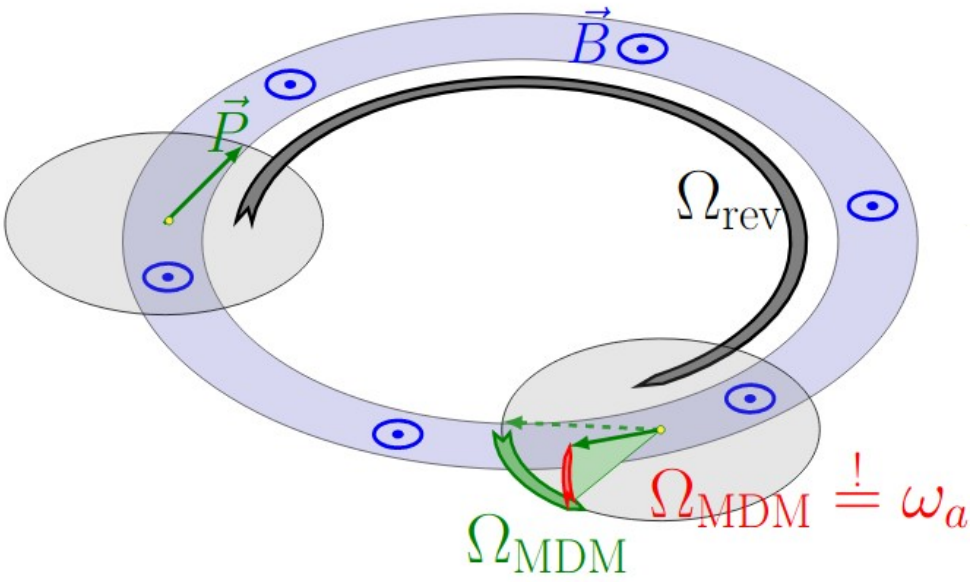
$$d = d_{DC} + d_{AC}\cos\left(\omega_a + \phi_0\right)$$

$$d_{AC} = a_0\, g_{ad\,\gamma}$$

$$\hbar\,\omega_a = m_a c^2$$

- Out-of-plane polarization build-up if

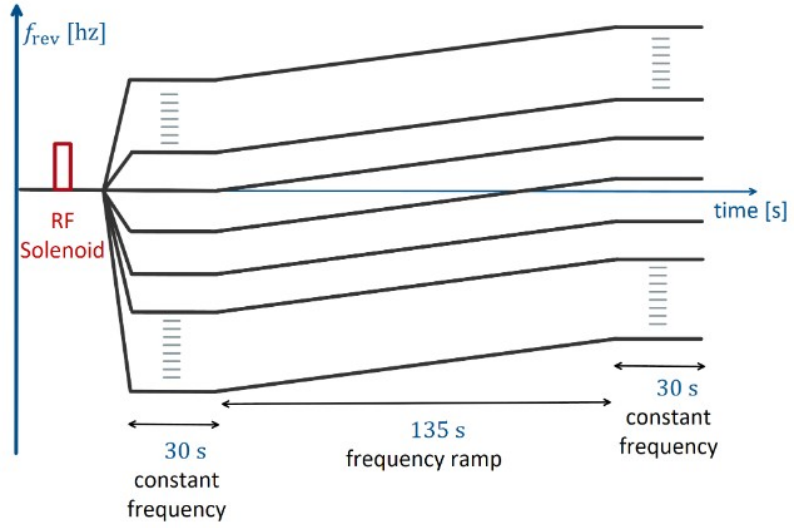
$$\Omega_{MDM} = \omega_a$$



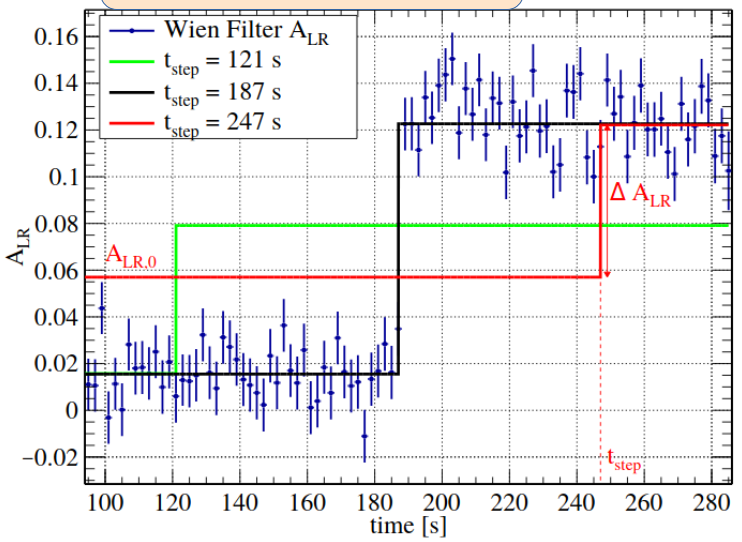
AXION / AXION LIKE PARTICLES (APL)

- Vary the spintune frequency in search for a resonance
- Scanned frequency range 119997 – 121457 Hz which correspond to axion / ALP mass range (4.96 – 5.02) 10^{-10} eV
- Measure polarization as a function of time
- Test with Wien filter for methodology:
  - scan to cross a fixed f_{WF}
- Step function fit

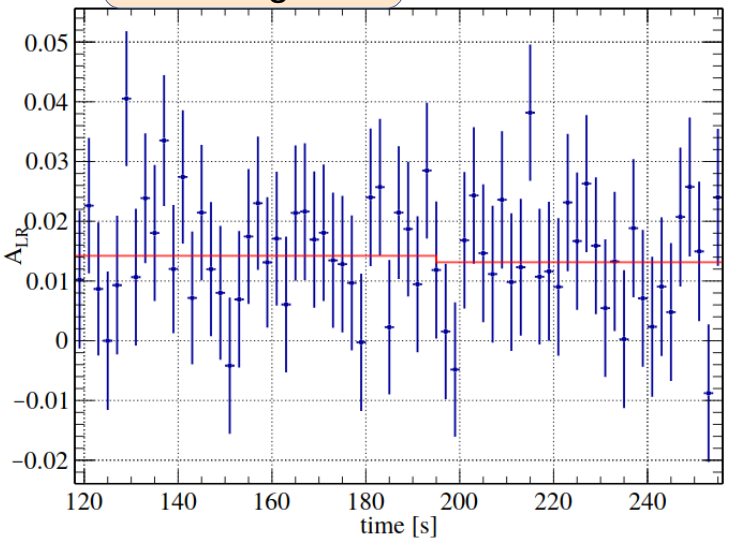
$$\Delta A_{LR} = -0.00105\,(233)$$



Fake signal induced by Wien filter

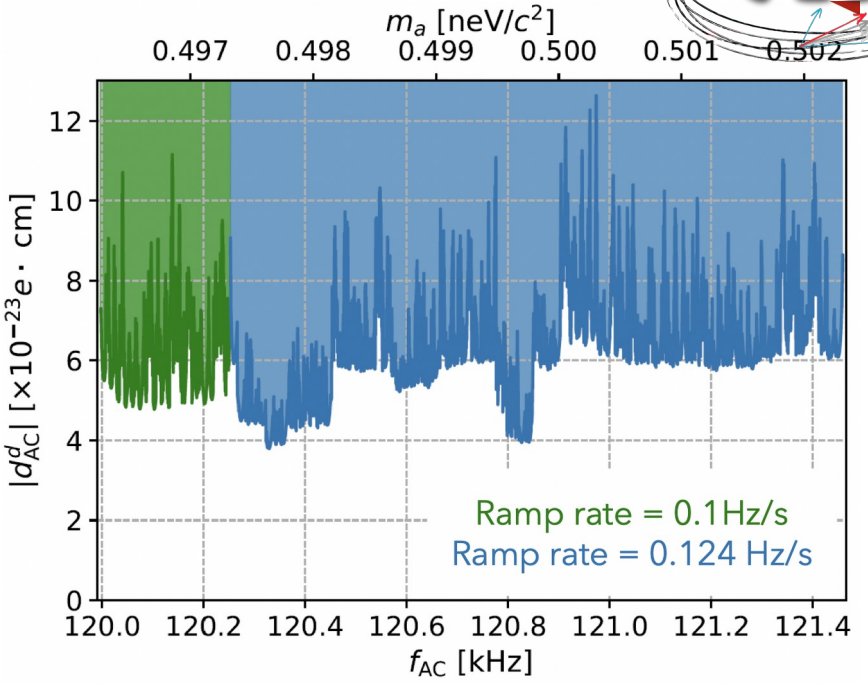


Axion / ALP searching run



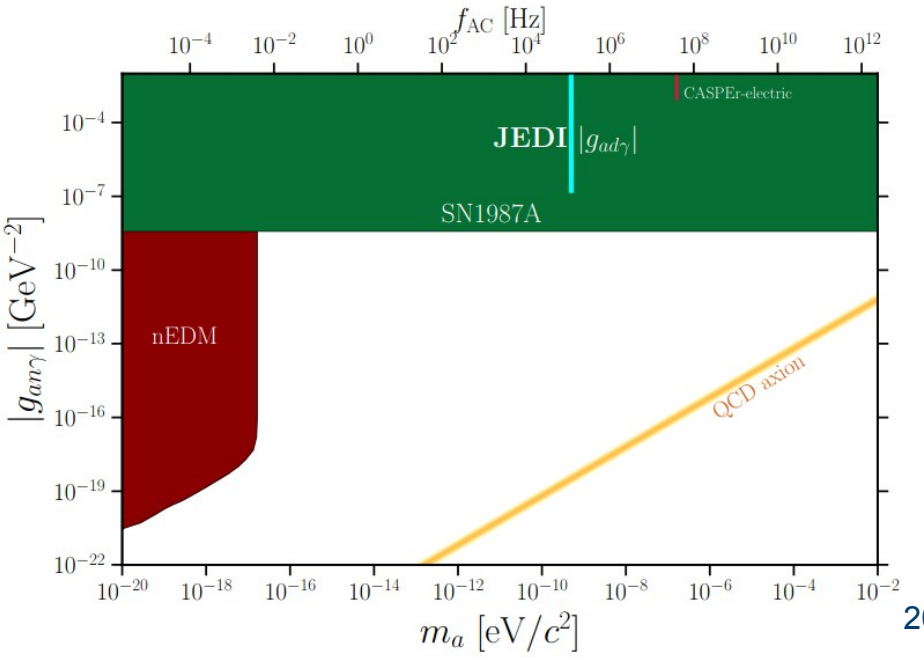
AXION / AXION LIKE PARTICLES (APL)

- Upper limits on the ALPs induced oscillating EDM
- Sensitivity of ~10^{-23} $e \cdot cm$ after only few days of data taking



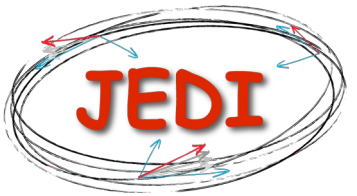
- Coupling of APL to deuteron EDM

$$|g_{ad\gamma}| < 1.7 \times 10^{-7}\, GeV^{-2}$$

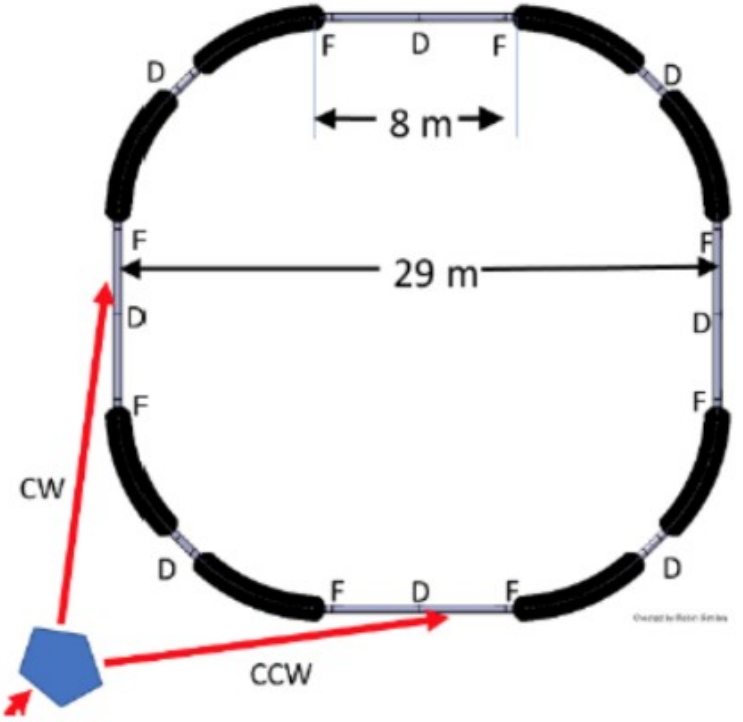


S. Karanth et al., "First Search for Axion-Like Particles in a Storage Ring Using a Polarized Deuteron Beam" 2022 https://arxiv.org/abs/2208.072931

STAGE 2: PROTOTYPE RING: PRESTO



- All electric E & combined E/B deflectors
- 100 m circumference
- protons of 30 MeV – all-electric beam operation
- protons of 45 MeV – frozen spin with additional vertical magnetic fields



Challenges:

- Only E & combined E+B deflection
- Storage time
- CW-CCW operation: orbit difference to pm
- Spin coherence time
- Polarimetry

Why we need the PTR prior to the dedicated ring:

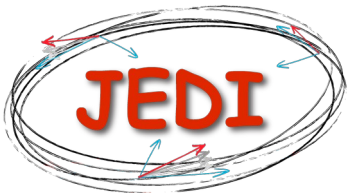
- To study open issues
- First direct proton EDM measurement

- Current status is summarized in CERN Yellow report

  * F. Abusaif et al., "Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study," CERN Yellow Report **257** (2021), **https://doi.org/10.23731/CYRM-2021-003**

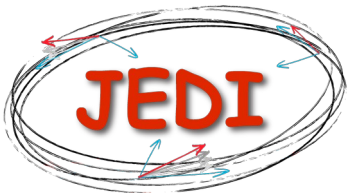
- Next step: CPEDM collaboration prepares Design Report

SUMMARY



- Charged hadron EDMs: Possibility to find sources of CP violation and to explain matter-antimatter asymmetry in the universe.
- Precursor experiments performed as a proof-of-principle of EDM measurement at storage rings.
- Method of searching for ALPs in storage ring demonstrated
  S. Karanth et al., “First Search for Axion-Like Particles in a Storage Ring Using a Polarized Deuteron Beam” 2022 https://arxiv.org/abs/2208.072931
- CERN Yellow Report prepared by CPEDM collaboration
  F. Abusaif et al., “Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study,” CERN Yellow Report **257** (2021), **https://doi.org/10.23731/CYRM-2021-003**
- Work on Design Report for PTR ongoing. Proposal PRESTO is out.
- COSY remains a unique facility for such studies

LIST OF IMPROVEMENTS



- Alignment campaigns of COSY magnet system
- Beam-based alignment
  PhD thesis T. Wagner
- New tool for fast tune and chromaticity measurement
  P. Niedermayer and B. Breitkeutz
- Slow control system
  I. Bekman and IKP4
- COSY signals and distribution was improved
  K. Laihem
- Rogowski coils at the Wien filter place
  F. Abusaif, R.Suvarna
- New JEDI polarimeter
  I. Keshelashvili and the polarimeter group
- 8 high-speed RF switchers to gate the WF power for one of the bunches
  pilot bunch technique
  J. Slim, A. Nass, F. Rathmann, G. Tagliente