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

MESON'21 19.05.2021 I VERA SHMAKOVA FOR THE JEDI COLLABORATION

JEDI

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CONTENTS

- Why are we going to measure EDMs of charged particles
- Time development of spin in storage rings
- EDMs are very small and hard to measure, so we use the step approach:
    - 1st step – use an existing storage ring (COSY) to start with
    - Next steps
- Summary & Outlook

MATTER-ANTIMATTER ASYMMETRY

- Why current universe is matter dominated?
- Big Bang produced the same amount of matter – antimatter
- Comparing the experiment:

$$\frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

V. Barger, et al, Phys.Lett.B566, 8 (2003)

expectation from SCM:

$$\frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-18}$$

W. Bernreuther, Lect. Notes Phys.591, 237 (2002)

- Preference of matter (A. Sakharov criteria)

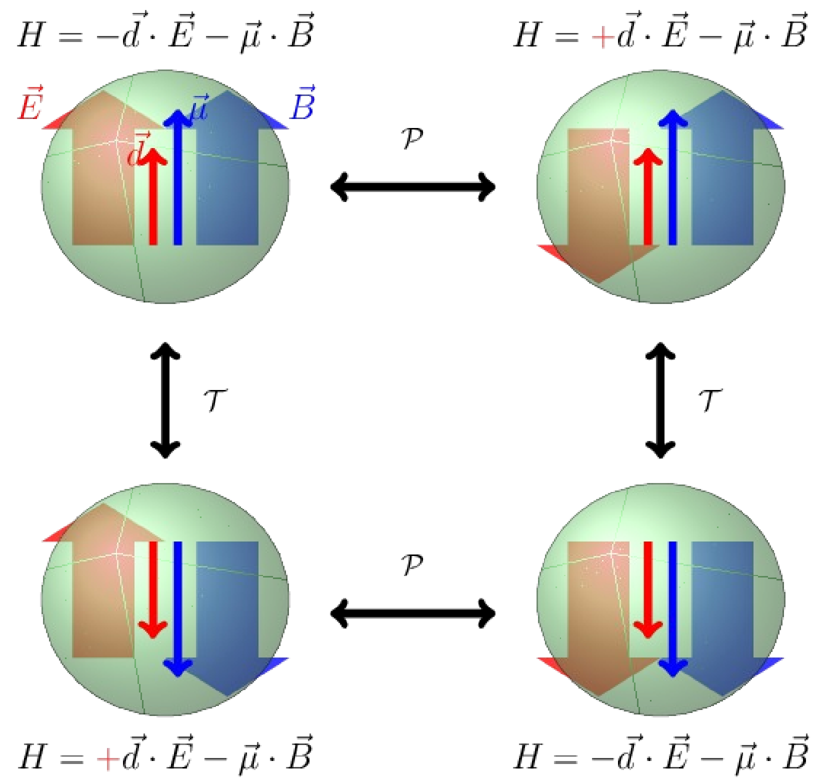
$\Rightarrow$ ***C*, *CP* violation**

There is *CP* violation in SM, but not sufficient magnitude $\Rightarrow$ **EDM**

ELECTRIC DIPOLE MOMENT

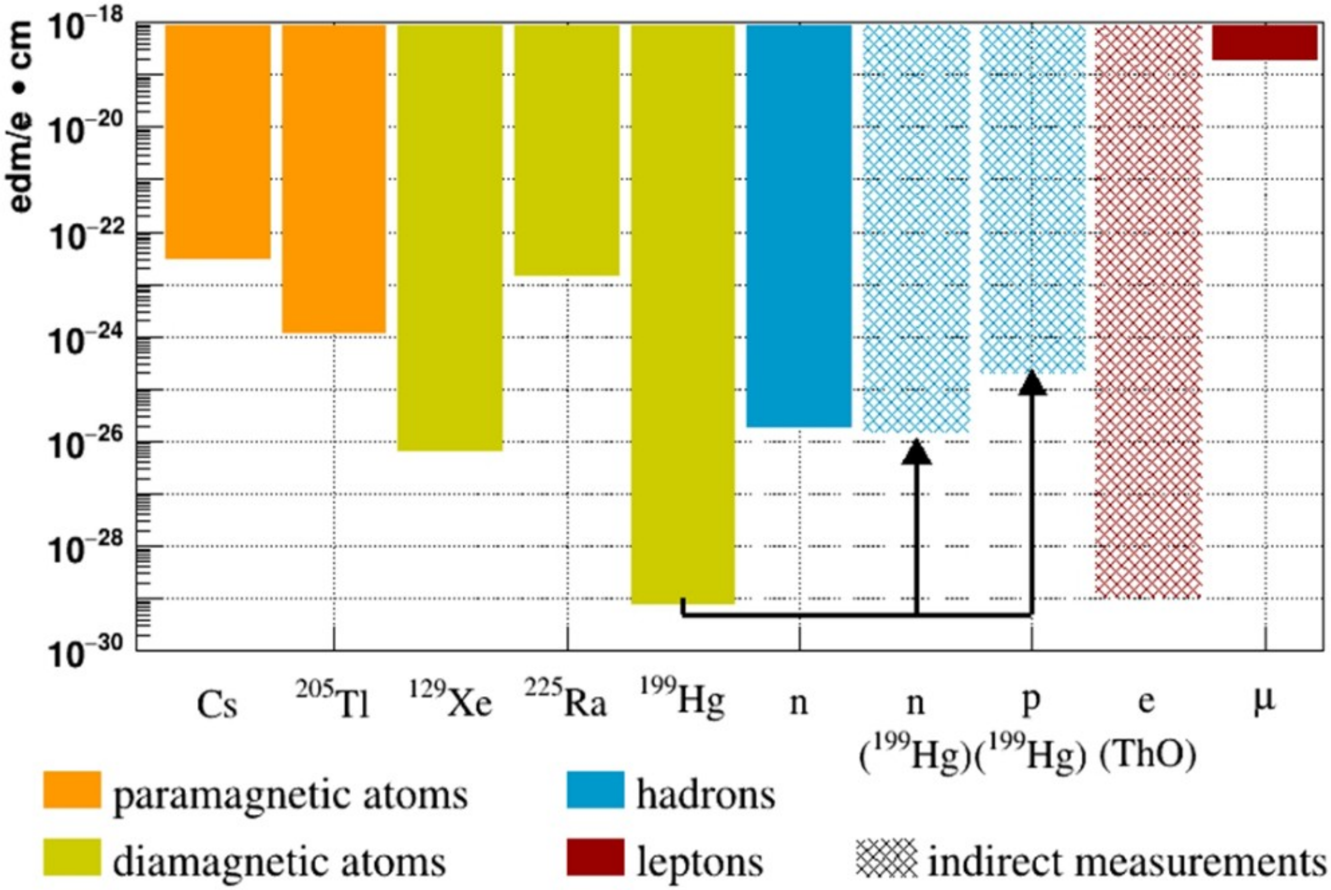
EDM violates both T, P symmetries

EDM violates CP symmetry
(if CPT conserved)



EDM is a probe for CP violation beyond the SM

EXISTING LIMITS ON EDM



CHARGED PARTICLE EDM

- No direct measurement for charged hadron EDMs
- Potentially higher sensitivity for charged hadrons (compared to neutrons):
    - longer lifetime
    - more stored polarized protons/deuterons
    - can apply larger electric fields in storage rings
- EDM of single particle type not sufficient to identify CPV source

EDM AT STORAGE RINGS

THOMAS - BMT EQUATION:

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

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

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

<u>At storage rings:</u> vertical $\boldsymbol{B}$ field, radial $\boldsymbol{E}$ field

Frozen spin case is if MDM has no impact on spin motion.
Momentum and spin in the absence of EDM would stay aligned.

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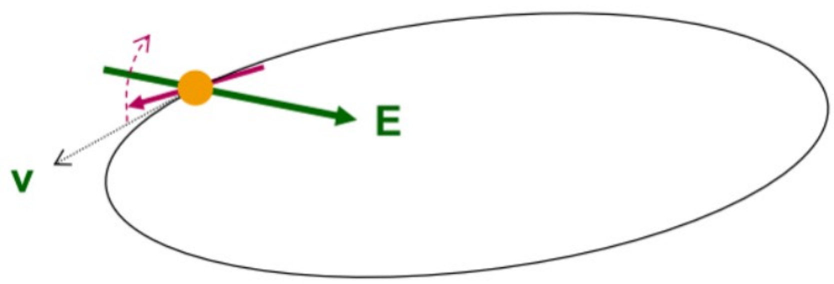
In case of purely electric ring:

- 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

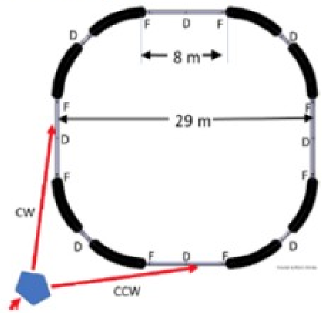
Stage 1

- precursor experiment

pure magnetic ring

Stage 2

- prototype ring

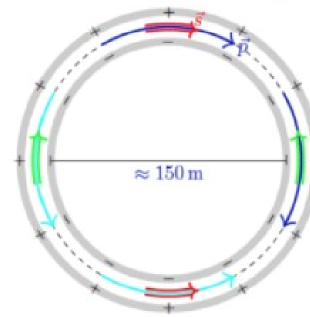


combined E/B ring

simultaneous CW-CCW beams

Stage 3

- dedicated storage ring



all electric proton ring

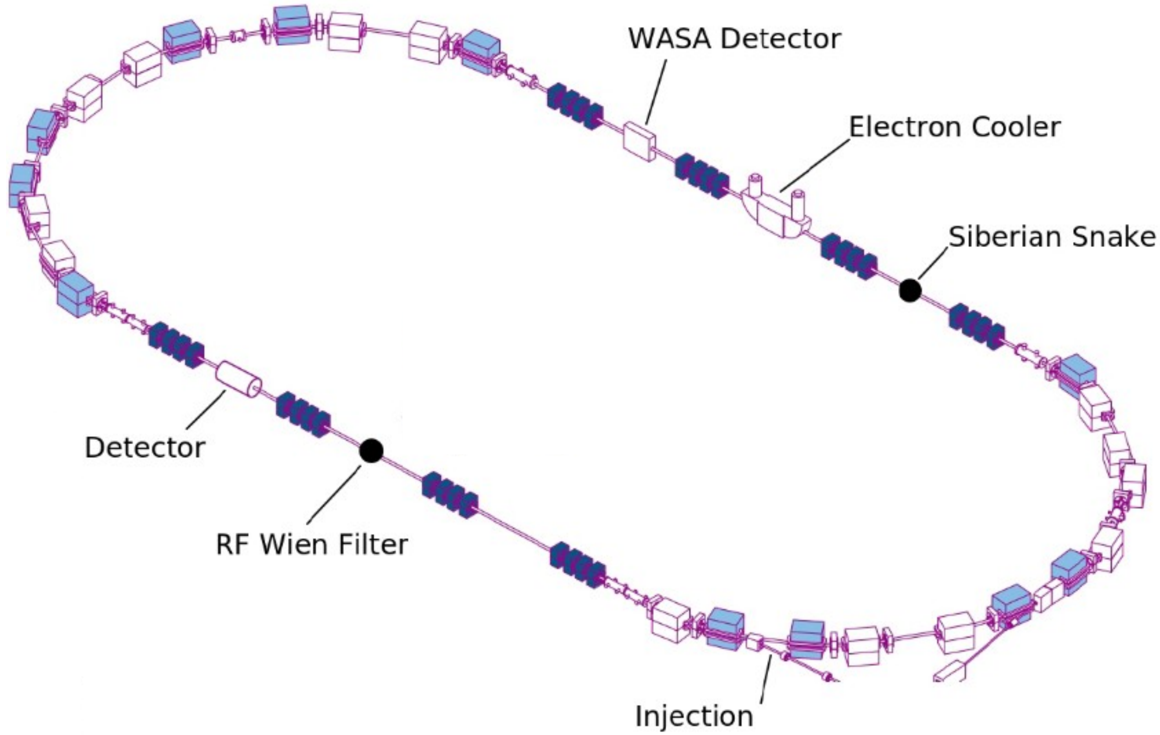
$\sigma_{EDM}/(e \cdot \mathrm{cm})$

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}

PRECURSOR EXPERIMENT AT COSY

COSY (Jülich, Germany)

- 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:

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

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

<u>At storage rings:</u> vertical $\boldsymbol{B}$ field, radial $\boldsymbol{E}$ field

MDM causes fast spin precession in horizontal plane

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

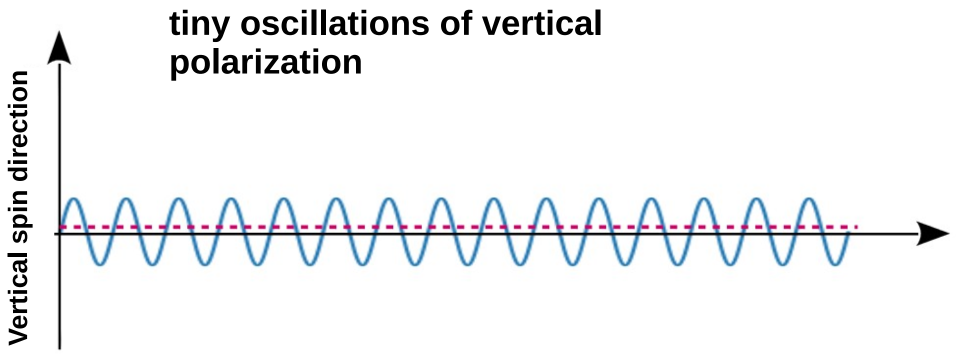
⇩

access to EDM

RF WIEN FILTER

In the magnetic ring
momentum ↑↑ spin ⇨ spin kicked up
momentum ↑↓ spin ⇨ spin kicked down

no accumulation of vertical asymmetry



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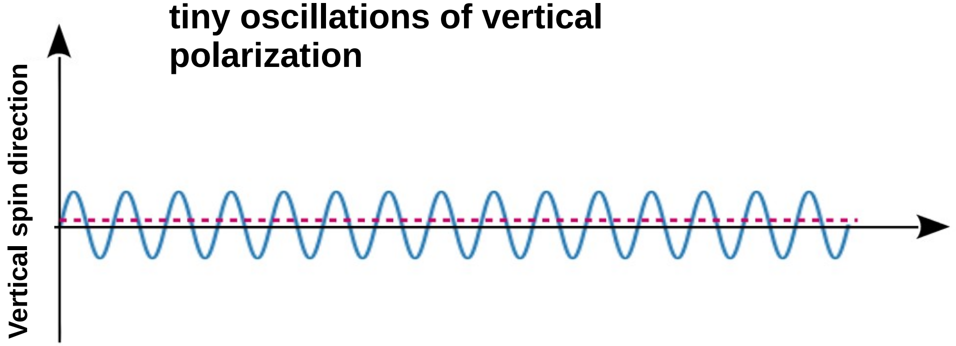
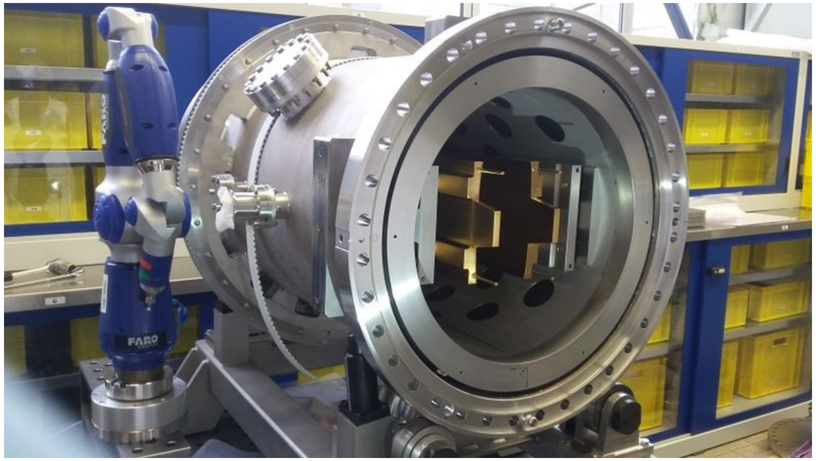


RF Wien filter

*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

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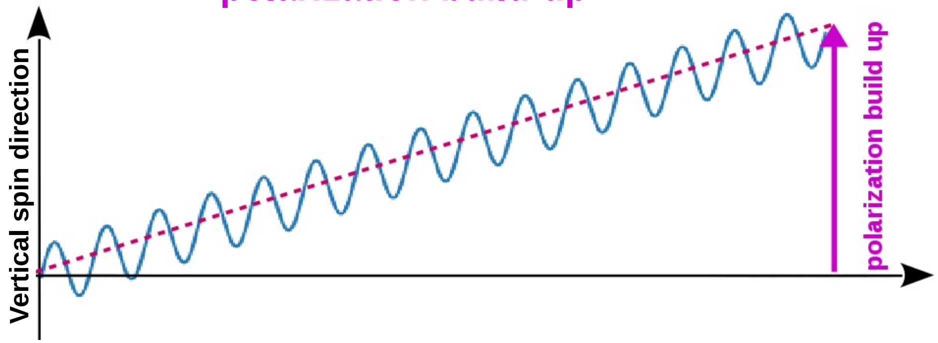
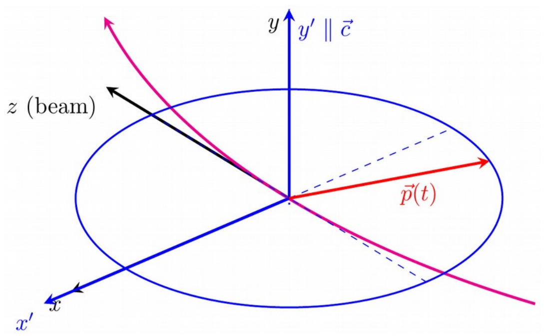
polarization build-up

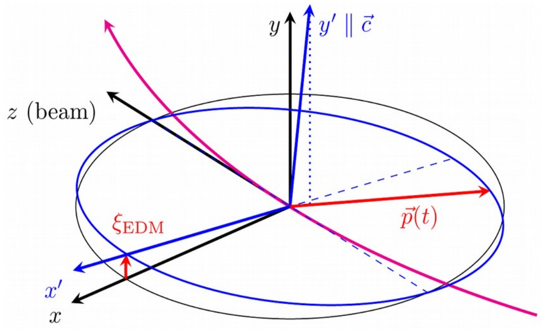


EFFECT ON PRECESSION AXIS

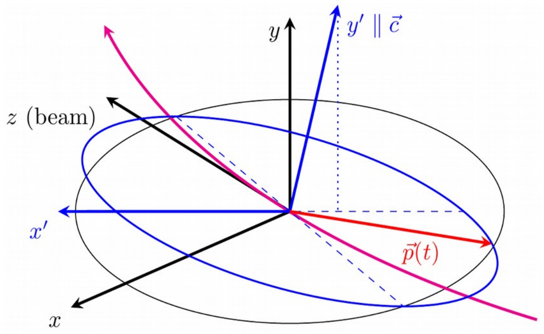
EDM absence case



EDM effect

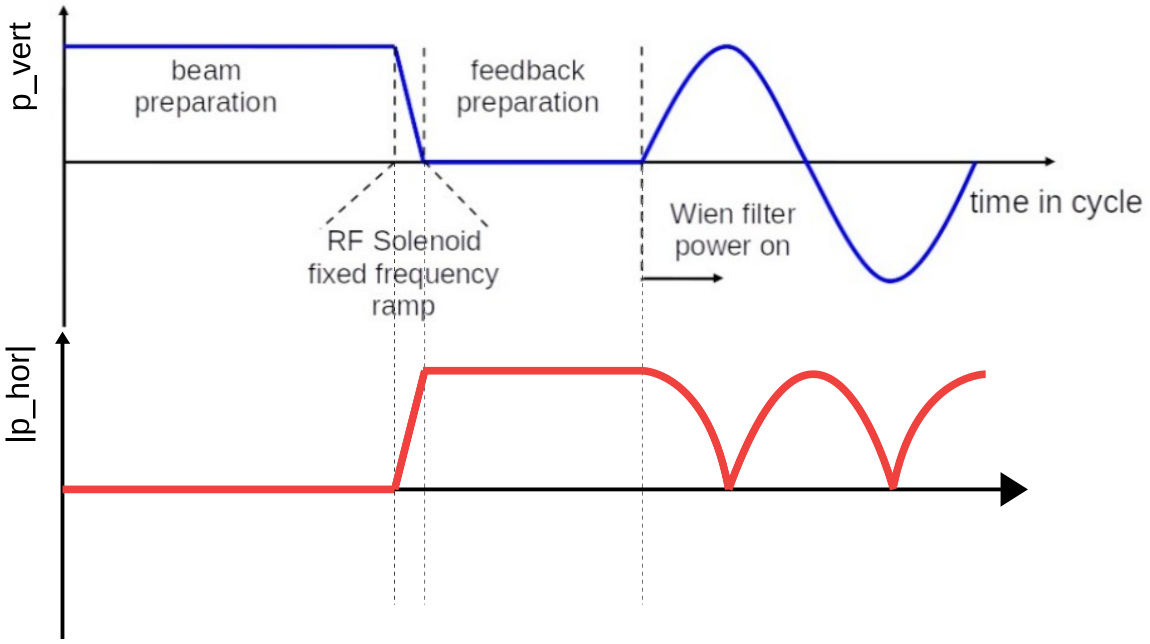


Magnetic misalignment effect



PRINCIPLE OF MEASUREMENTS

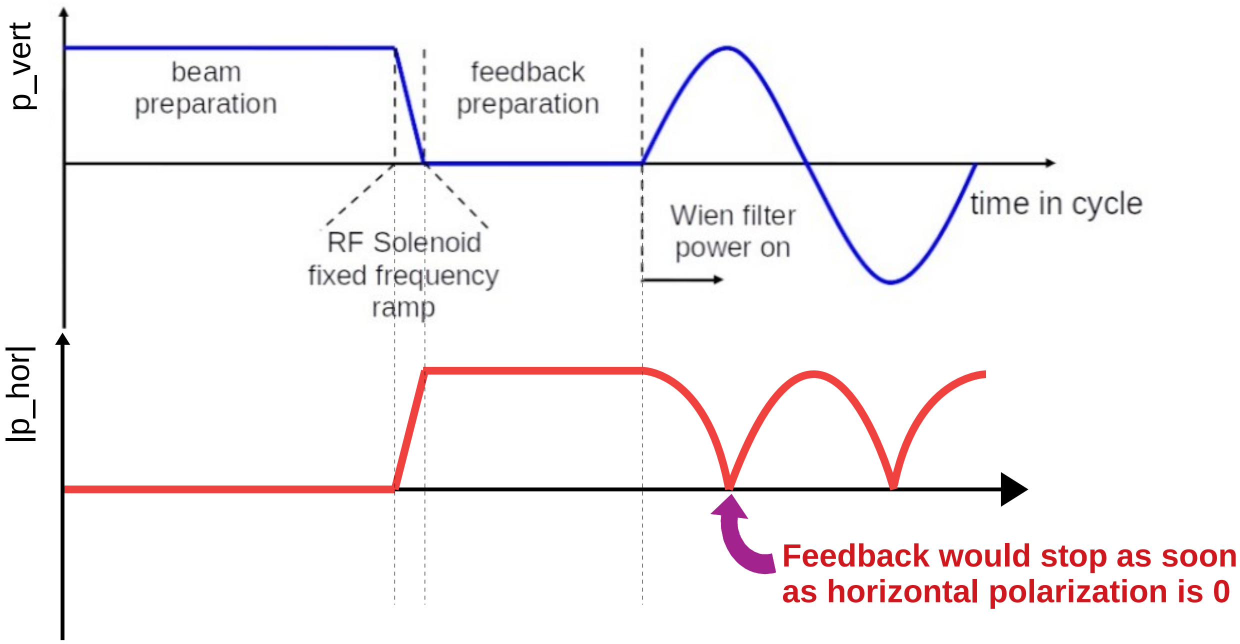
The basic workflow

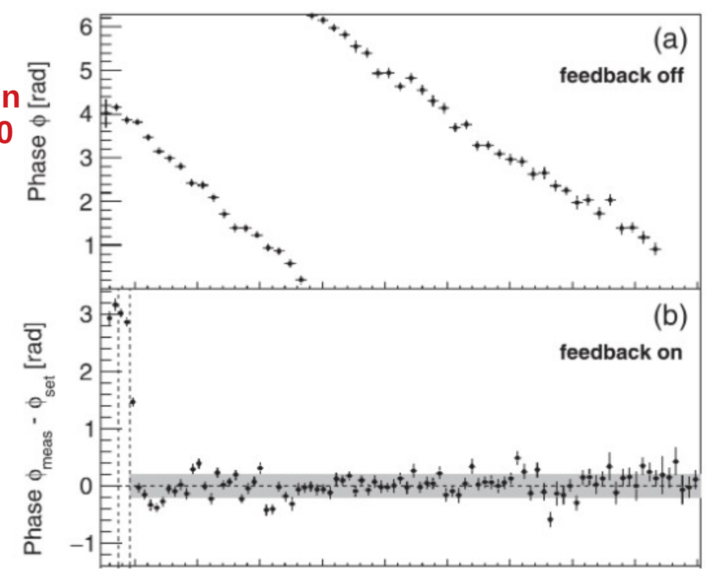


- Coherent ensembles in ring plane ➡ time of the horizontal polarization decoherence - “spin coherence time” - has to be longer then a measurement
- Spin precesses with 120 kHz.
- Wien filter operates on resonance f = 871.430 kHz
- Phase lock between spin precession and Wien filter

PRINCIPLE OF MEASUREMENTS

The basic workflow





- Feedback monitors spin precession phase and adjust WF frequency to maintain the relative phase between spin precession and Wien filter

- an error of 0.2 rad

FIRST RESULTS

During the first precursor (November'18)

31 points measured

2 weeks of pure measurement

Parametric resonance strength
based on initial slope

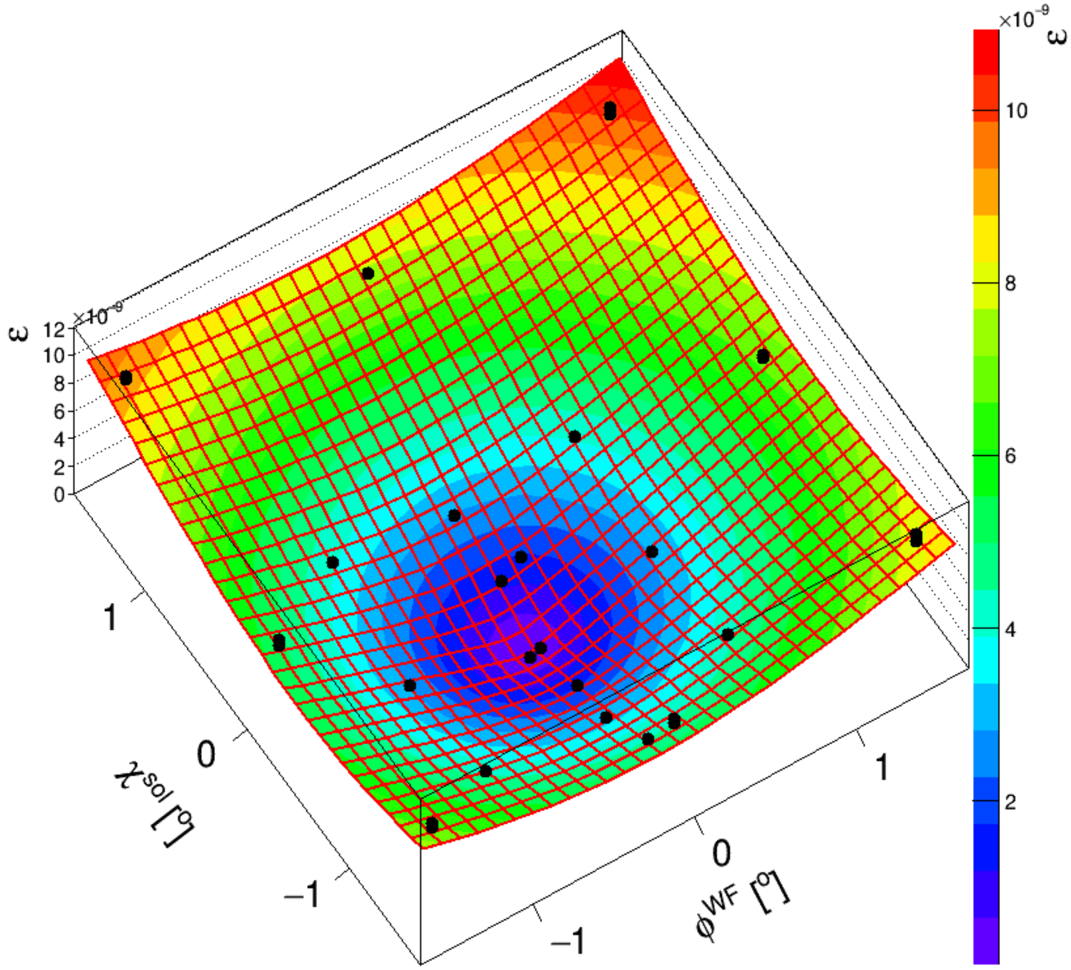
$$\varepsilon^{EDM} = \frac{\Omega^{P_Y}}{\Omega^{rev}}$$

Orientation of precession axis at location of RF Wien filter determined from the minimum of the surface:

φ_0^{wf} = -3.80 +- 0.05 mrad

X_0^{sol} = -5.51 +- 0.05 mrad

Spin tracking calculations should provide the orientation of precession axis without EDM



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 and V. Hejny
- Rogowski coils at the Wien filter place
  PhD thesis F. Abusaif
- 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

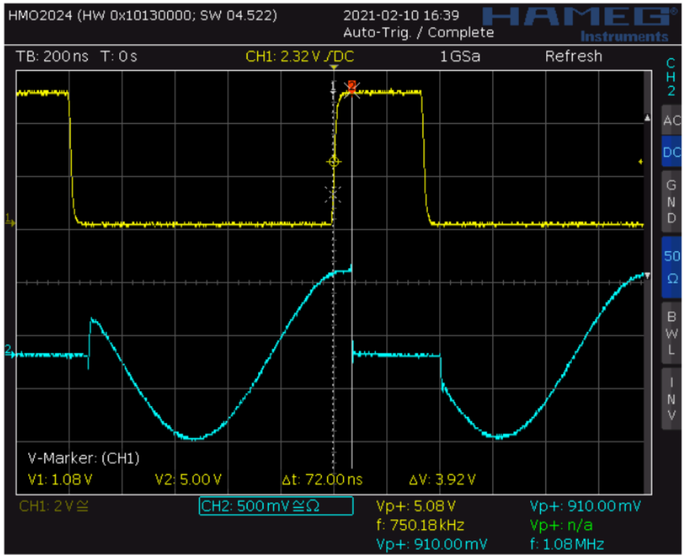
PRECURSOR RUN II

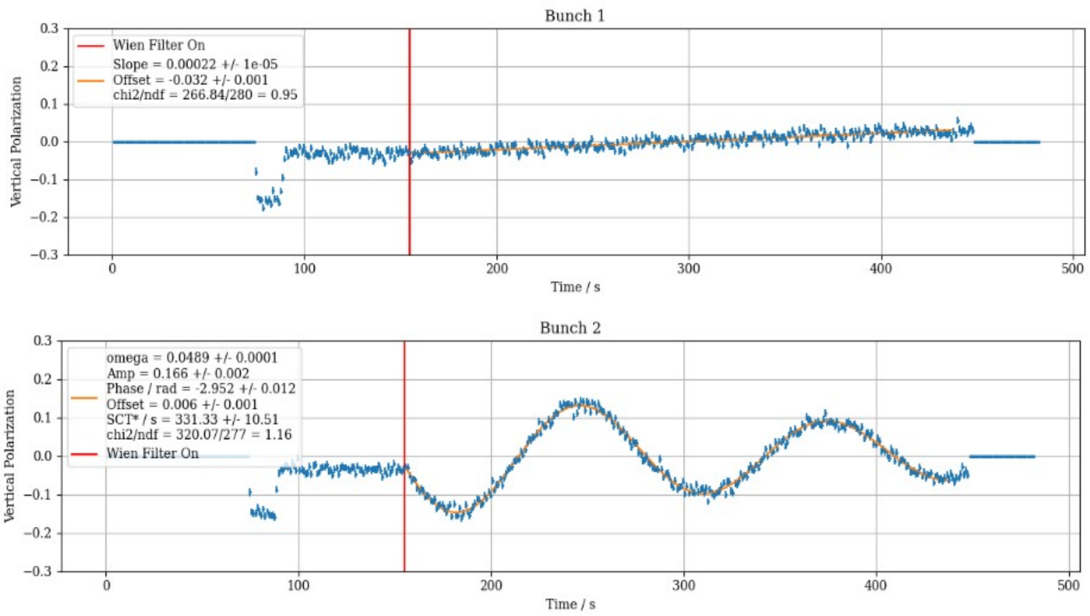
Precursor run II March-April 2021

- 3.5 weeks of data taking
- 9 Maps
- Two methods were successfully used:
    - Initial polarization build up
    - Pilot bunch

Pilot bunch method:

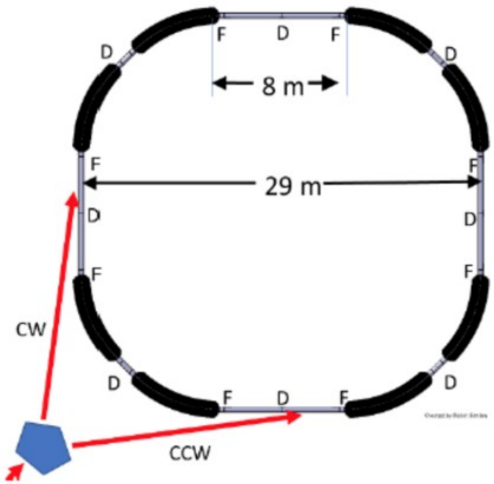
- 8 high-speed RF switchers to gate the WF power for one of two bunches
- Capable of short switch time ~ few ns
- Bunch 2 feels the power and oscillate
- Bunch 1 is used as pilot bunch for phase locking





NEXT STEP PROTOTYPE RING

- 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," 2019.https://arxiv.org/abs/1912.07881

- Next step: CPEDM collaboration prepares Technical Design Report

PROTOTYPE RING

- All electric E & combined E/B deflectors
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- P of 30 MeV – all-electric beam operation
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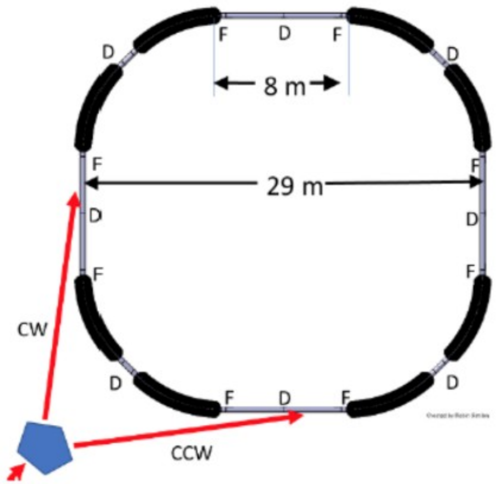

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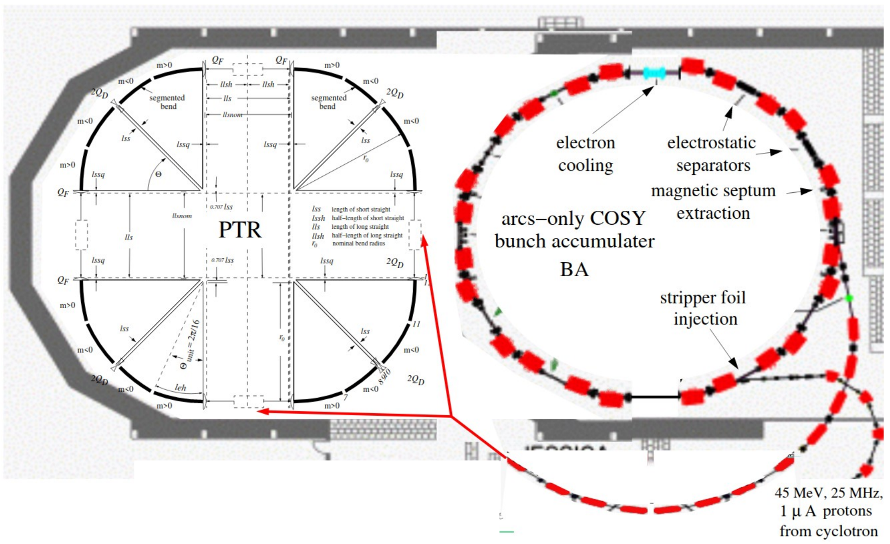
Cost efficient option to use COSY

- If placed in the COSY Hall, the arcs-only COSY rebuild as the bunch accumulator

R. Talman talk, WE-Heraeus-Seminar Towards Storage Ring Electric Dipole Moment Measurements, 2021



SUMMARY

- Why search for charged hadron EDMs? Possibility to find sources of CP violation and to explain matter-antimatter asymmetry in the universe.
- Precursor experiments performed is a proof of principle of EDM measurement at storage rings. Analysis of the data is ongoing.
- COSY remains a unique facility for such studies.
- Proposal for prototype EDM storage ring prepared by CPEDM.
- The work on Technical Design Report for PTR is ongoing.