



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

01.09.2021

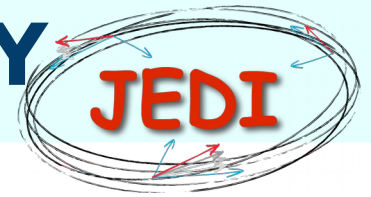
VERA SHMAKOVA FOR THE JEDI COLLABORATION





- Why measure EDMs of charged particles
- Time development of spin in storage rings
- EDMs very small and hard to measure, use stepwise approach:
 - Use existing storage ring (COSY) to start with
 - Stages with increasing sensitivity:
 - **Precursor experiment**
 - PTR
 - Final ring
- Summary & Outlook

MATTER-ANTIMATTER ASYMMETRY



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

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

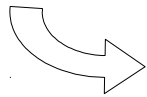
$$\frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

with expectation from SCM:

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

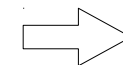
$$\frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-18}$$

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



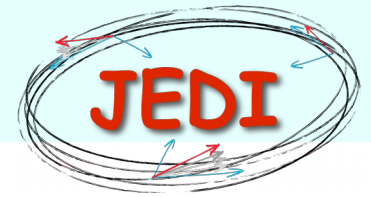
C, CP violation

There is *CP* violation in SM, but not sufficiently large



EDM

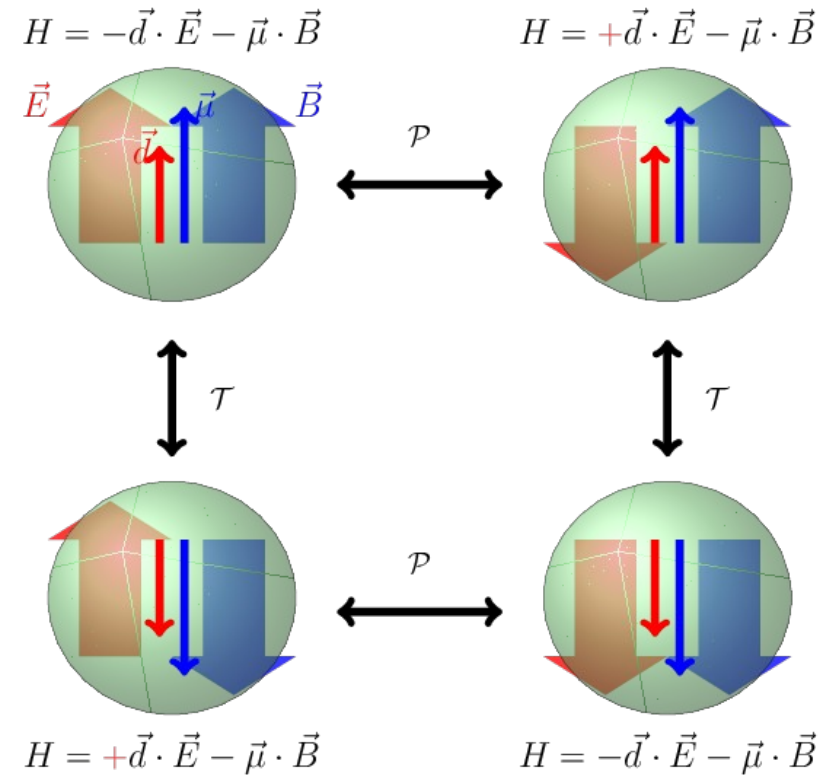
ELECTRIC DIPOLE MOMENT



EDM violates both T, P symmetries

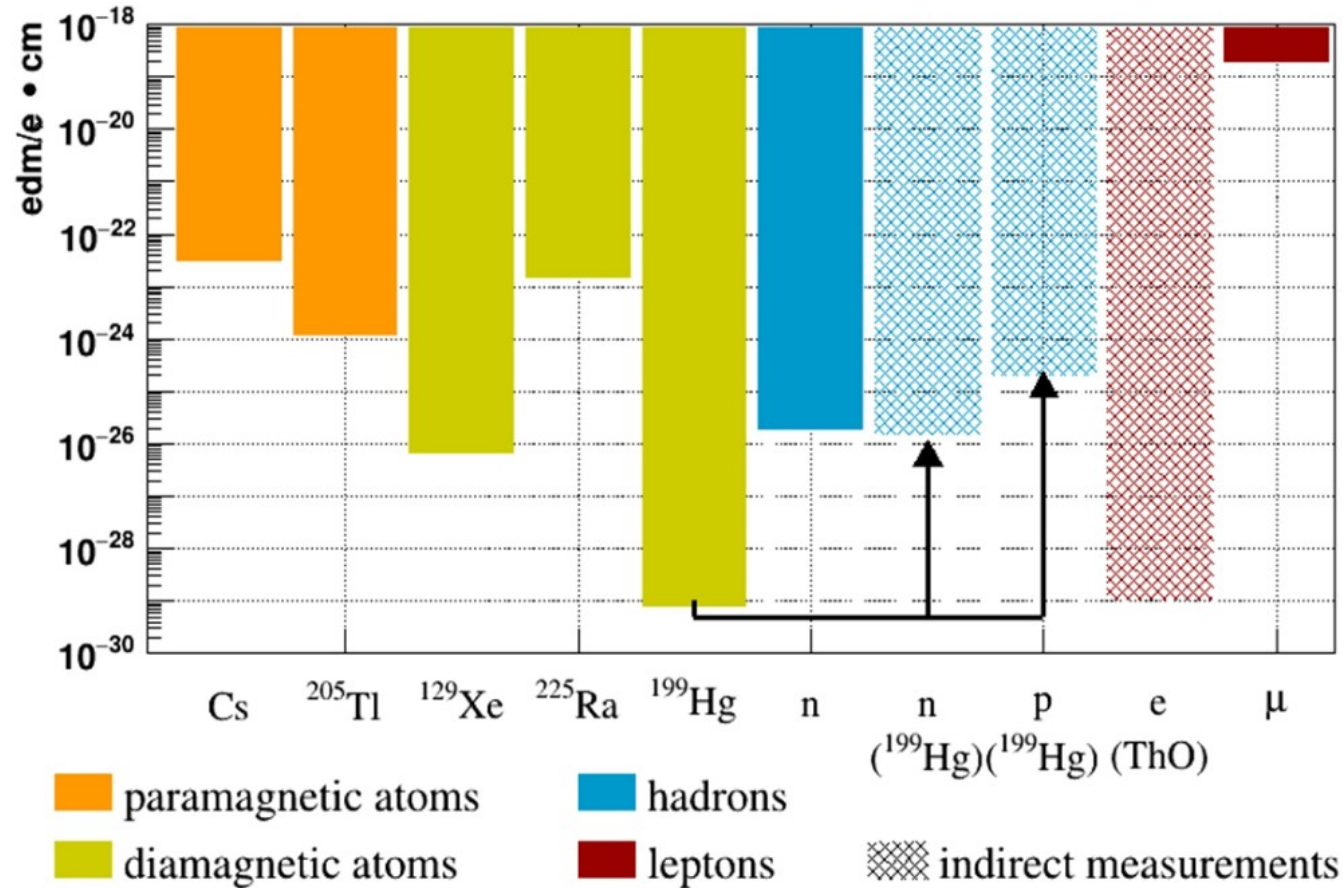
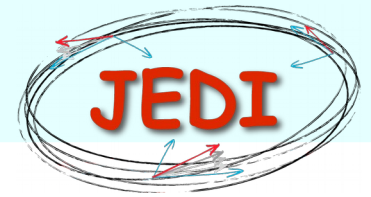


EDM violates CP symmetry
(if CPT conserved)



EDM is a probe for CP violation beyond the SM

EXISTING LIMITS ON EDM

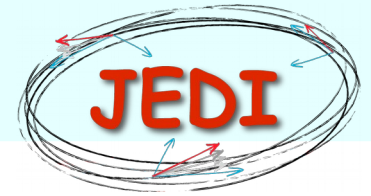


* F. Abusaif et al., "Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study," 2019. <https://arxiv.org/abs/1912.07881>



- 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:

$$\frac{d\vec{S}}{dt} = [\vec{\Omega}_{MDM} - \vec{\Omega}_{cycl} + \vec{\Omega}_{EDM}] \times \vec{S}$$
$$\vec{\Omega}_{MDM} - \vec{\Omega}_{cycl} = -\frac{q}{m} \left\{ G\vec{B} - \left(G - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right\}$$
$$\vec{\Omega}_{EDM} = -\frac{\eta q}{2mc} \{ \vec{E} + c \vec{\beta} \times \vec{B} \}$$

At storage rings: vertical \mathbf{B} field, radial \mathbf{E} field

Frozen spin: momentum and spin in the absence of EDM would stay aligned

EDM AT STORAGE RINGS



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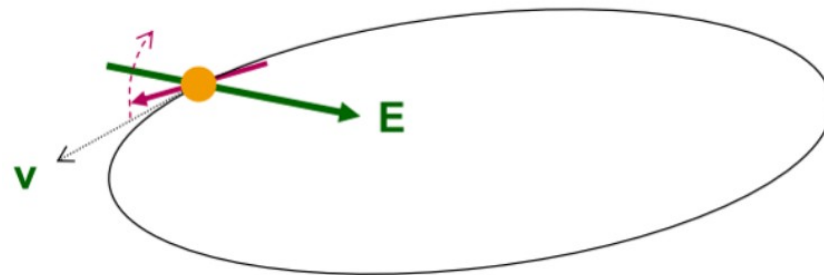
At storage rings: vertical \mathbf{B} field, radial \mathbf{E} field

Frozen spin: momentum and spin in the absence of EDM would stay aligned

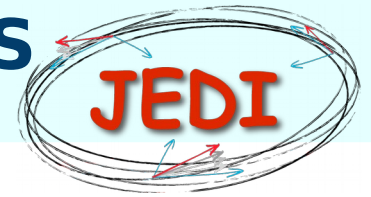
In case of purely electric ring:

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

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



EDM FOR CHARGED PARTICLE IN 3 STAGES



Stage 1

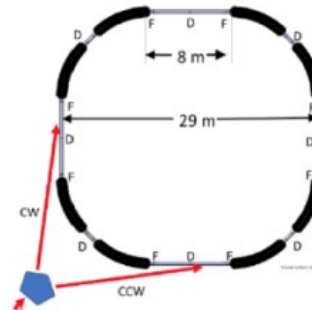
- precursor experiment



pure magnetic ring

Stage 2

- prototype ring



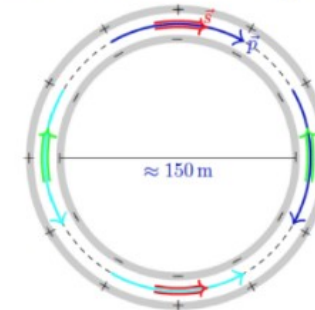
combined E/B ring

simultaneous CW-CCW beams

frozen spin

Stage 3

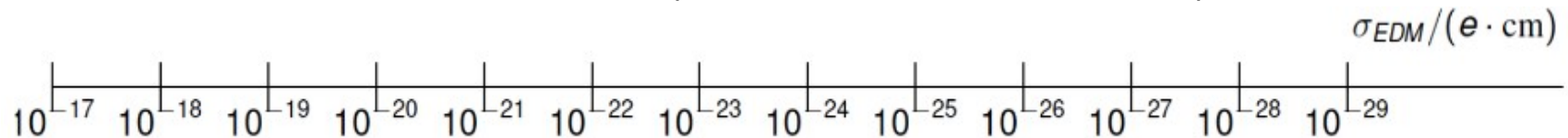
- dedicated storage ring



all electric proton ring

simultaneous CW-CCW beams

frozen spin

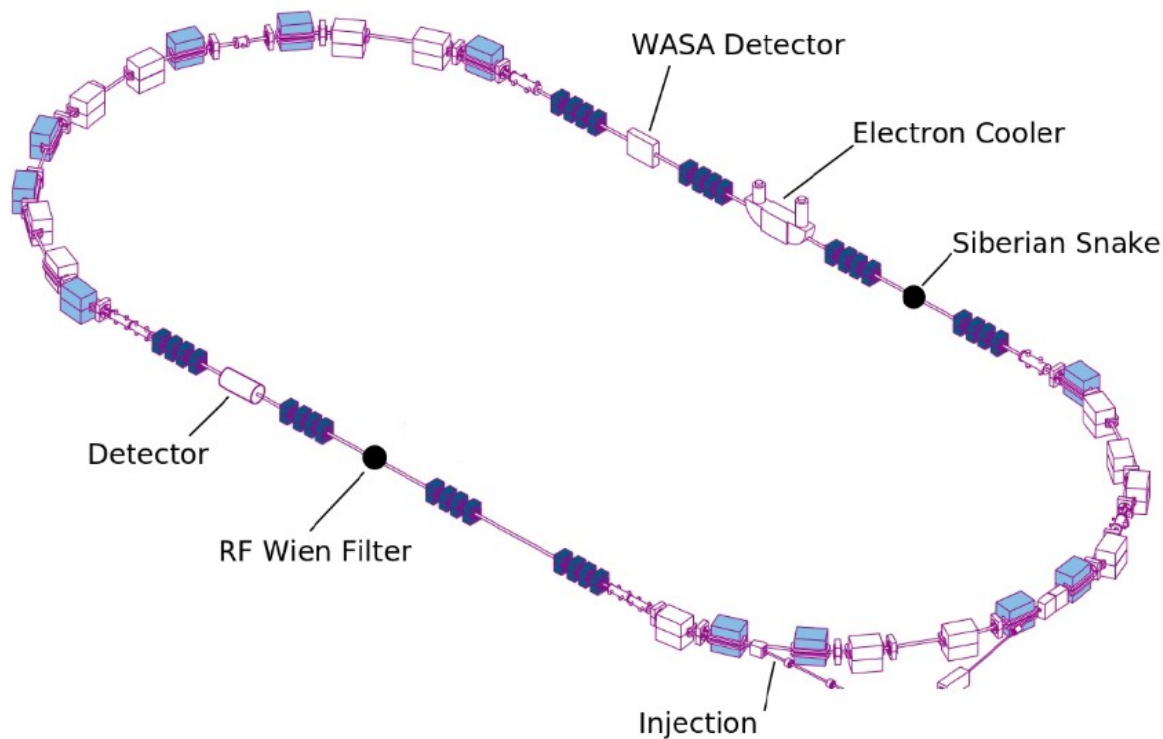


PRECURSOR EXPERIMENT AT COSY



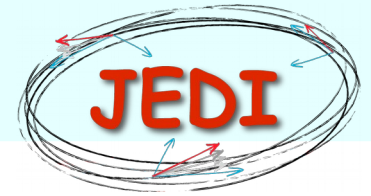
COSY (Jülich, Germany)

- magnetic storage ring
- polarized protons and deuterons
- Momenta $p = 0.3 - 3.7 \text{ GeV}/c$



**Starting point for
EDM measurement**

EDM AT MAGNETIC RING



THOMAS - BMT EQUATION:

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

At storage rings: vertical \mathbf{B} field, radial \mathbf{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

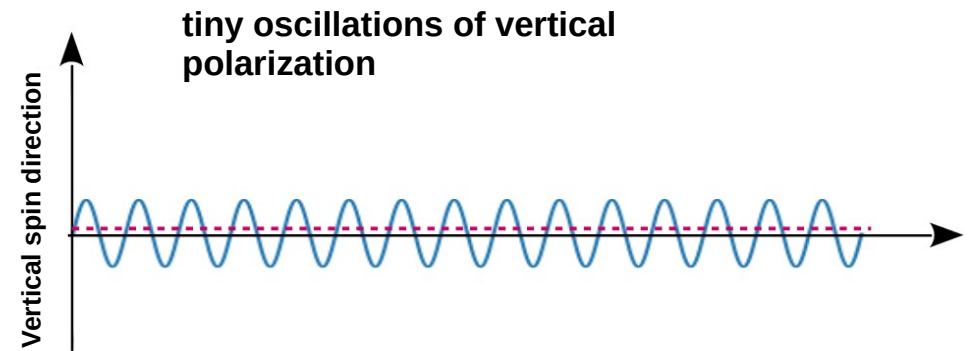
RF WIEN FILTER



In the magnetic ring

momentum $\uparrow\uparrow$ spin \rightarrow spin kicked up
momentum $\uparrow\downarrow$ spin \rightarrow spin kicked down

\downarrow
no accumulation of vertical asymmetry

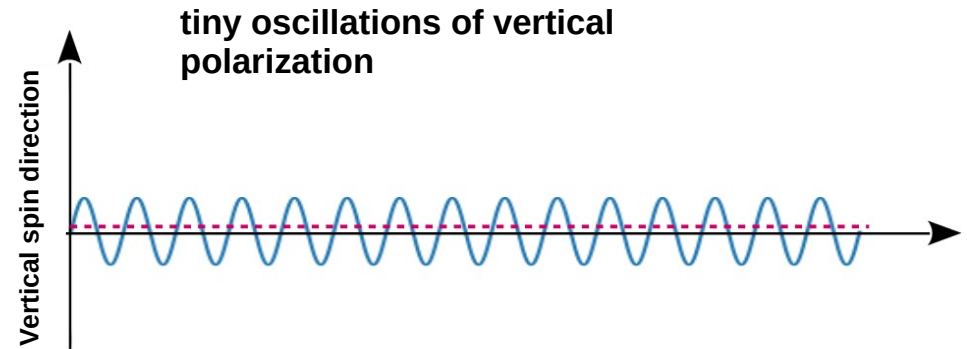


RF WIEN FILTER



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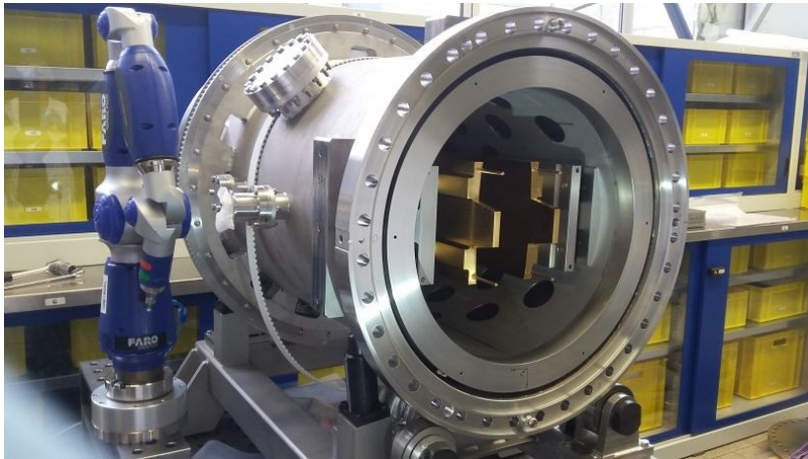


RF Wien filter

Heberling, Höscher and J. Slim

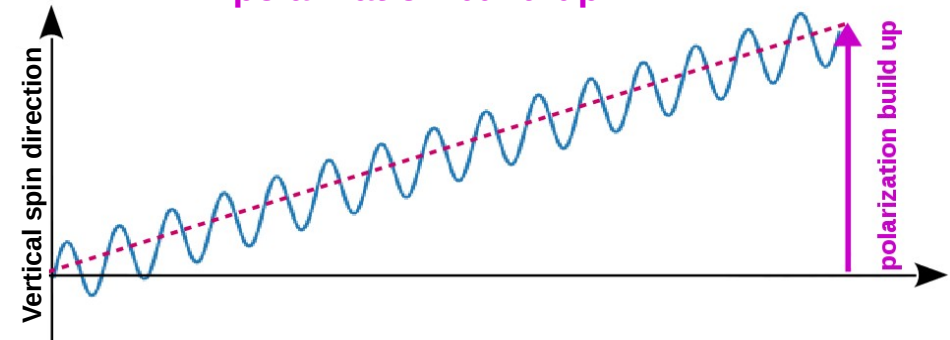
J. Slim et al. Nucl. Instrum. Methods Phys. Res. A 828, 116 (2016)

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

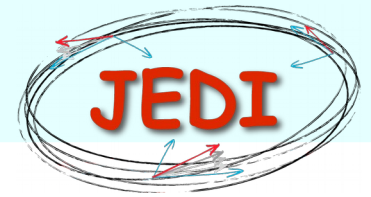


phase lock between spin precession and RF Wien filter

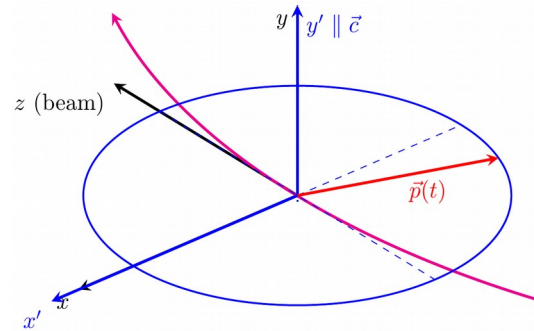
polarization build-up



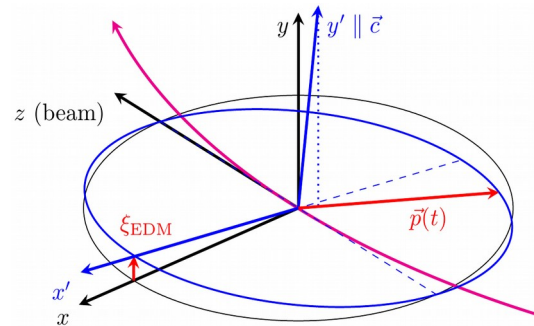
EFFECT ON PRECESSION AXIS



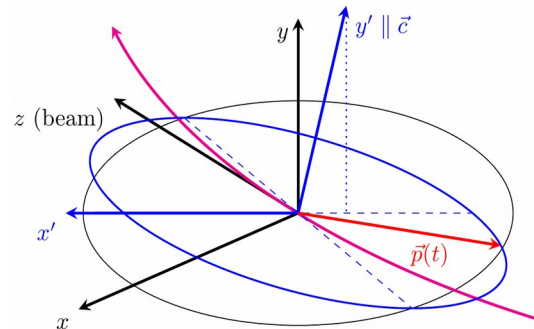
EDM absent



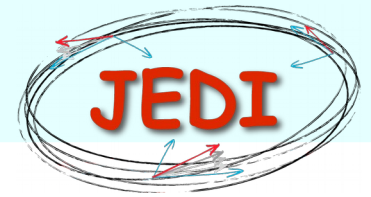
Pure EDM effect



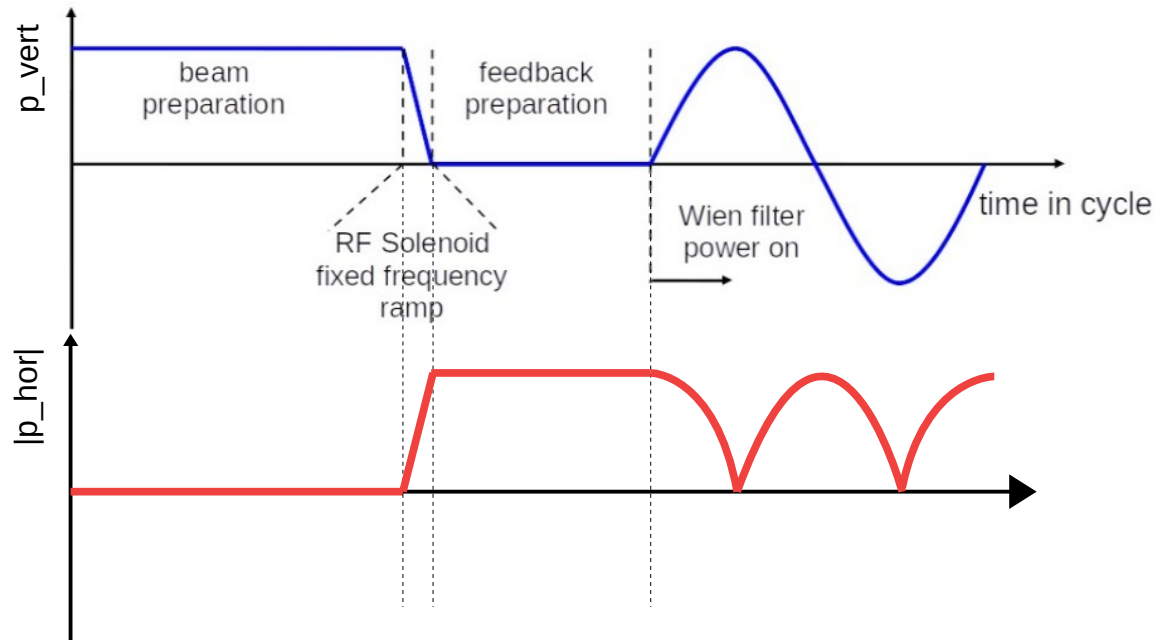
EDM + magnetic misalignments



PRINCIPLE OF MEASUREMENTS

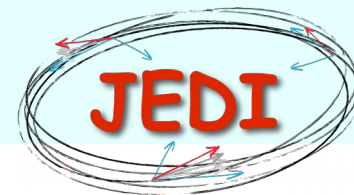


The basic workflow

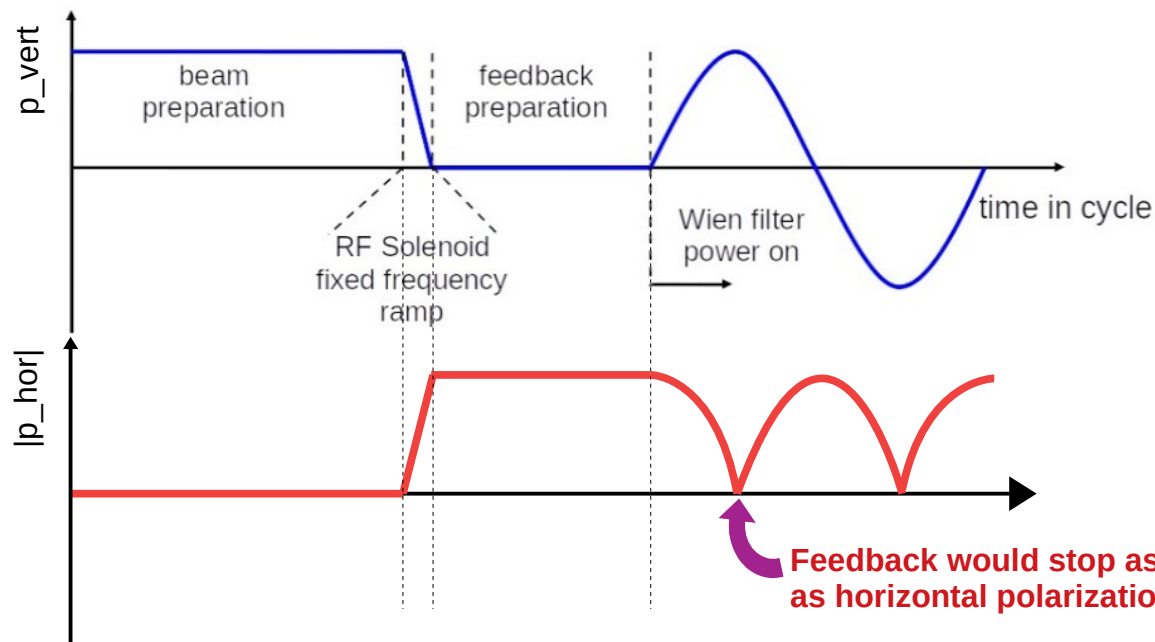


- Coherent ensembles in ring plane → time of the horizontal polarization decoherence - “spin coherence time” - has to be longer than a measurement
- Spin precesses with 120 kHz.
- Wien filter operates on resonance $f = 871.430$ kHz
- Phase lock between spin precession and Wien filter

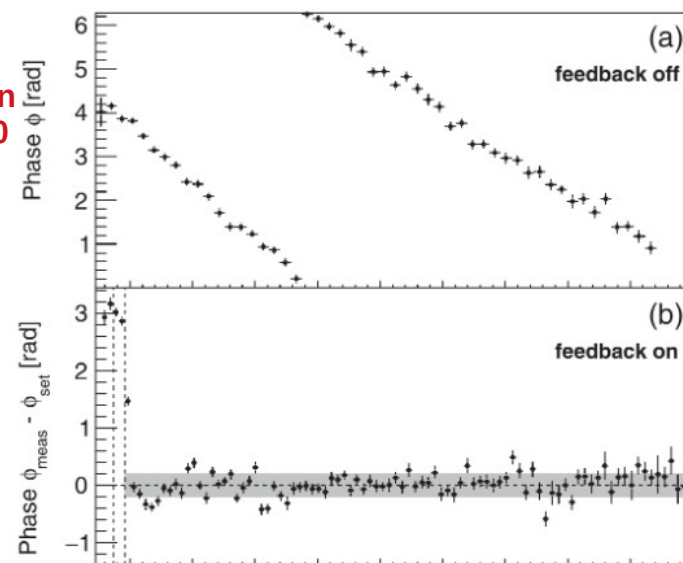
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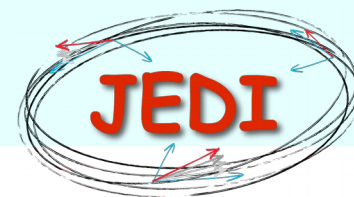
The basic workflow



- 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



Precursor experiment I November 2018:

31 points measured

2 weeks of pure measurement

Parametric resonance strength based on initial slope

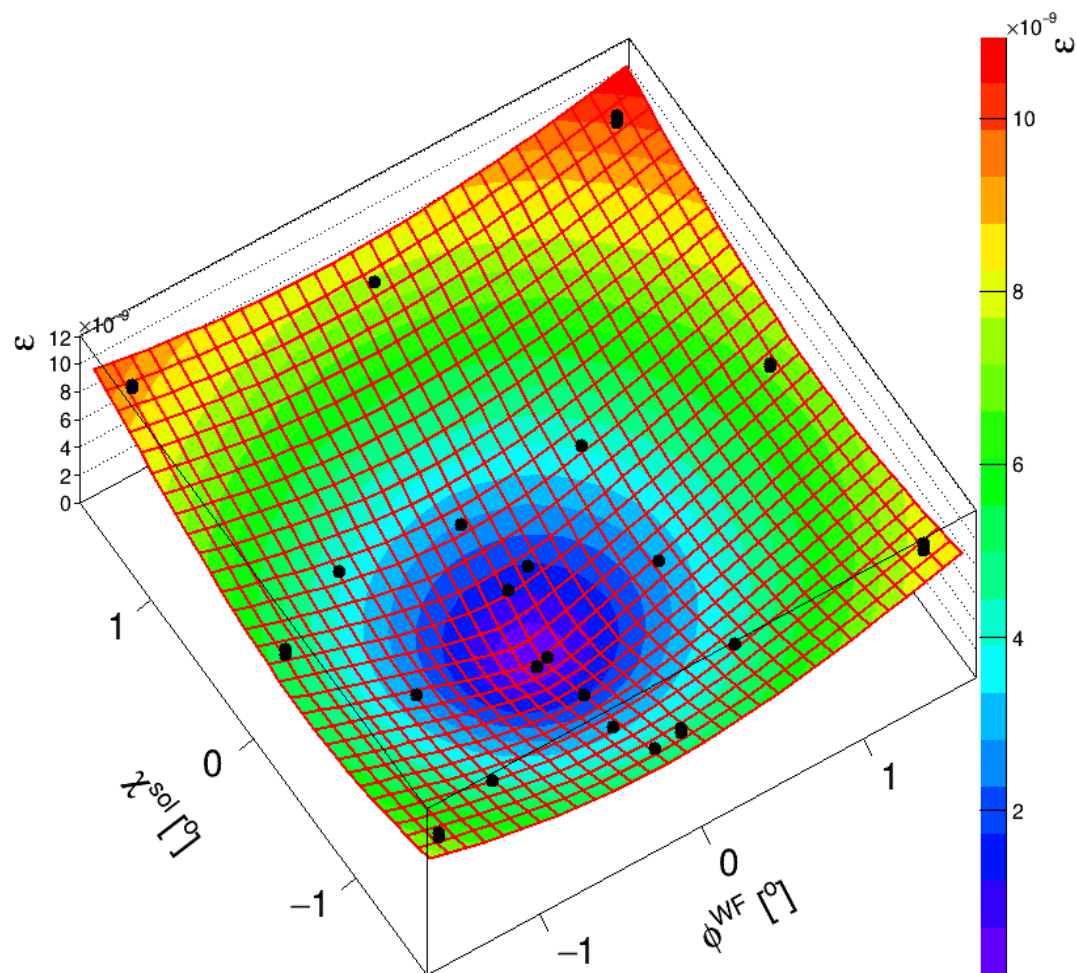
$$\varepsilon^{EDM} = \frac{\Omega^{Py}}{\Omega^{rev}}$$

Minimum of the surface shows orientation of precession axis:

$$\varphi_0^{wf} = -3.80 \pm 0.05 \text{ mrad}$$

$$\chi_0^{sol} = -5.51 \pm 0.05 \text{ mrad}$$

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



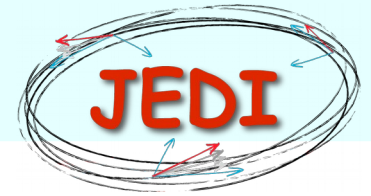
LIST OF IMPROVEMENTS



- 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
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

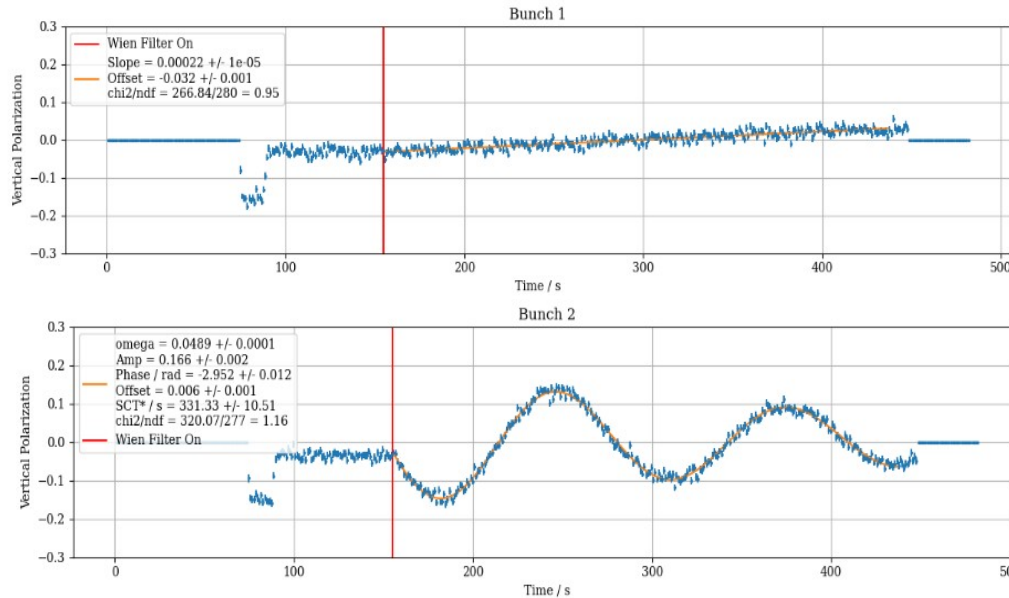
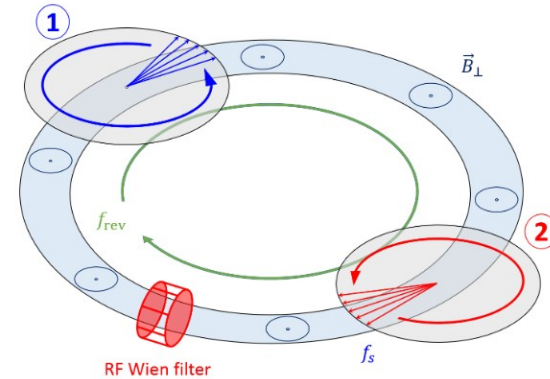
PRECURSOR RUN II

GATING OF THE BUNCH



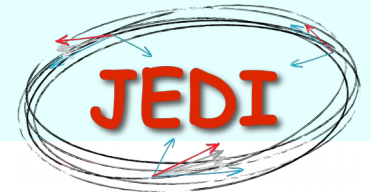
Precursor experiment II March-April 2021

- 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 switches to gate the WF power for one of two bunches
 - Capable of short switch time \sim few ns
 - Bunch ① and ② orbit at $f_{\text{rev}} \approx 750$ kHz
 - coherent ensembles in ring plane
 - precessing at $f_s \approx 120$ kHz
 - Bunch ② feels the power and oscillate
 - Bunch ① is used as pilot bunch for phase locking

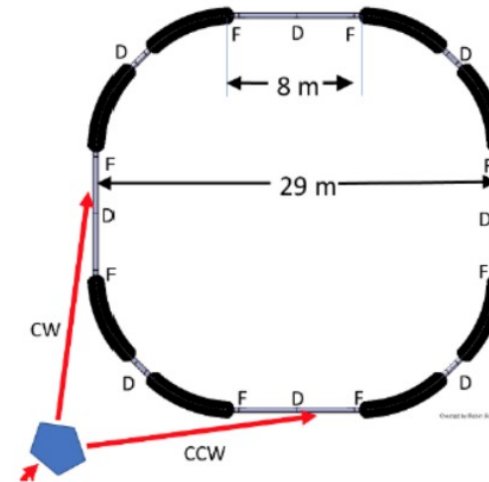
STAGE 2: PROTOTYPE RING



- 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

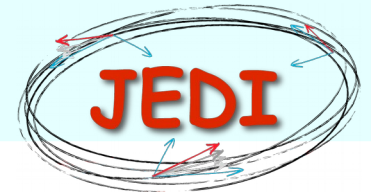
Challenges:

- 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



- 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. Analysis of data ongoing.
- COSY remains a unique facility for such studies.
- Proposal for prototype EDM storage ring prepared by CPEDM.
- Work on Technical Design Report for PTR ongoing.