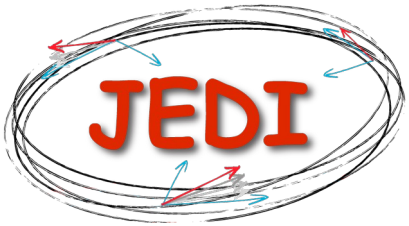
MEASUREMENT OF THE DEUTERON ELECTRIC DIPOLE MOMENT USING A STORAGE RING

VERA SHMAKOVA FOR THE JEDI COLLABORATION



2/02/2024

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)

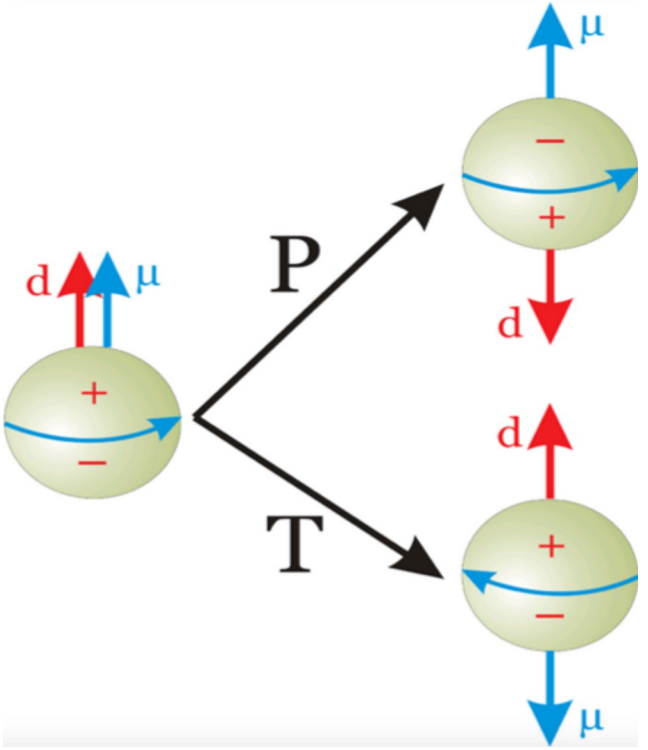
_CP_ violation

- *CP* violation in SM is not sufficient

ELECTRIC DIPOLE MOMENT

- EDM violates both T, P symmetries

- EDM violates CP symmetry (if CPT conserved)



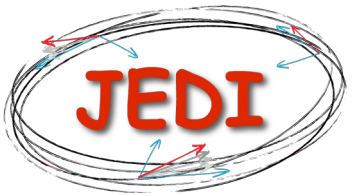
- EDM may possibly contain the missing cornerstone to explain the matter-antimatter asymmetry

$$H = -\mu\vec{\sigma}\cdot\vec{B} - d\vec{\sigma}\cdot\vec{E}$$

$$\mathcal{P}: \quad H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$

$$\mathcal{T}: \quad H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$

EDM AT STORAGE RINGS

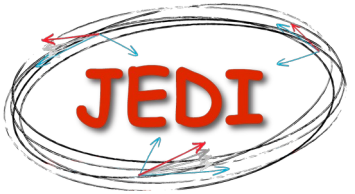


THOMAS - BMT EQUATION:

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

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

EDM AT STORAGE RINGS



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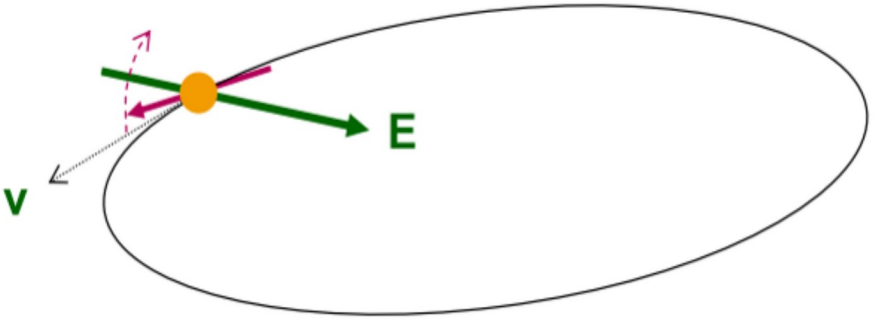
($\vec{B} \to 0$, $\vec{\beta} \to 0$)

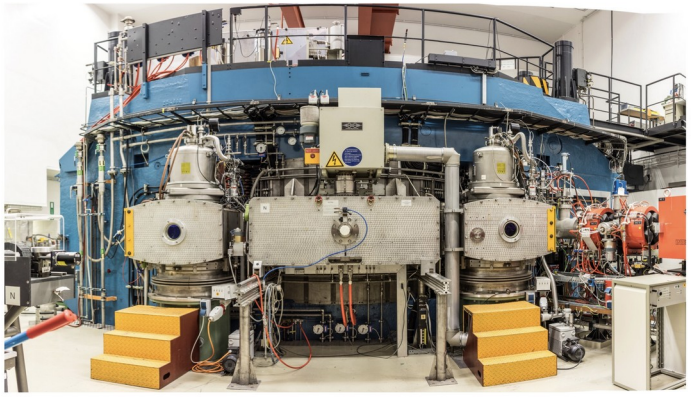
In case of purely electric ring:

- magnetic field is absent
- momentum is chosen that term $(G - \frac{1}{\gamma^2 - 1}) = 0$
- in the absence of EDM spin stay aligned to momentum → **frozen spin condition**
- radial electric field causes the spin to precess out of the plane linearly



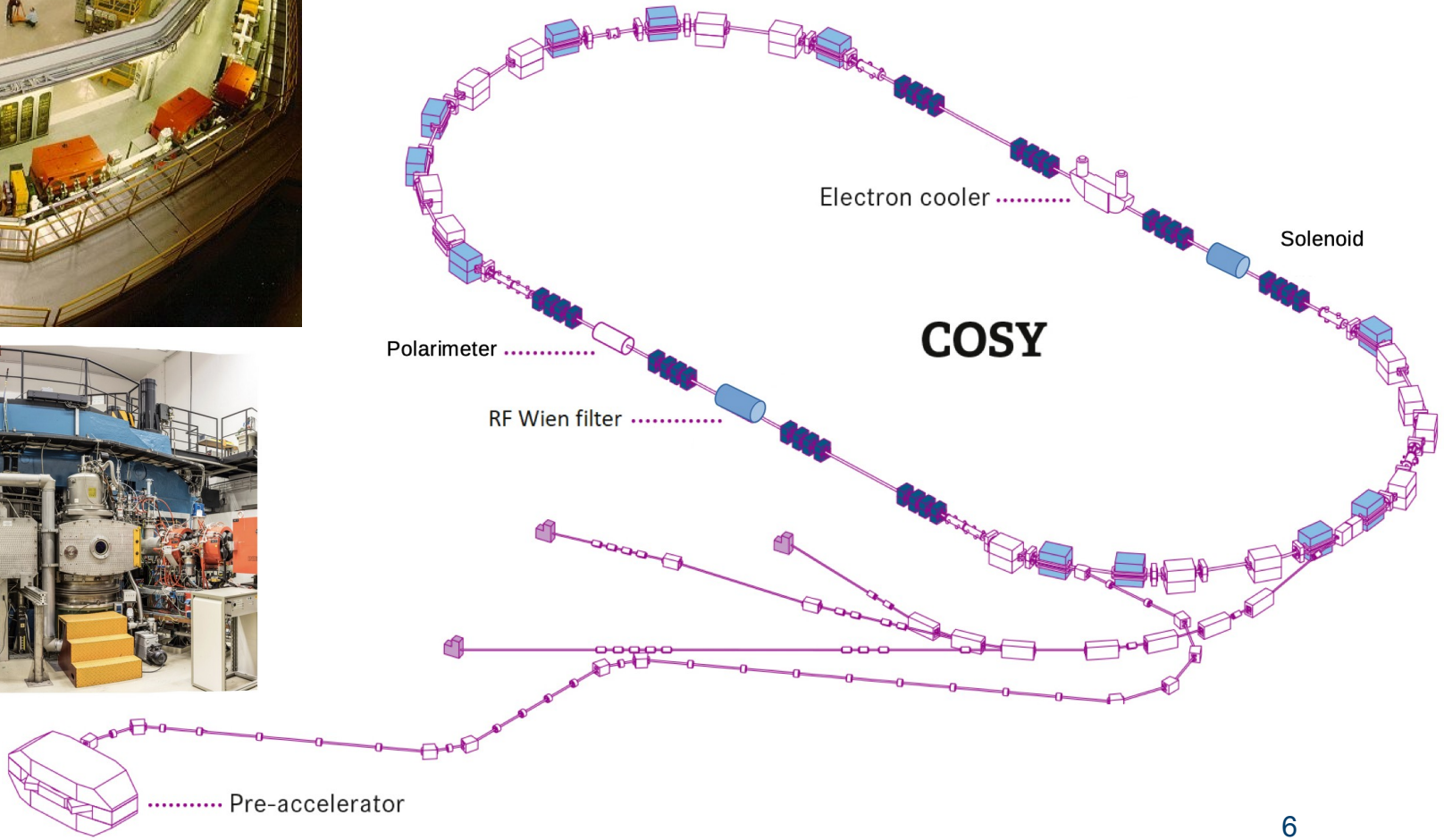
⇨ polarization build-up $p_y(t) \propto d$

PRECURSOR EXPERIMENT AT COSY

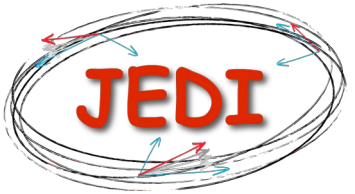


COoler SYnchrotron COSY:

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



EDM AT MAGNETIC RING



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

MDM causes fast spin precession in horizontal plane

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

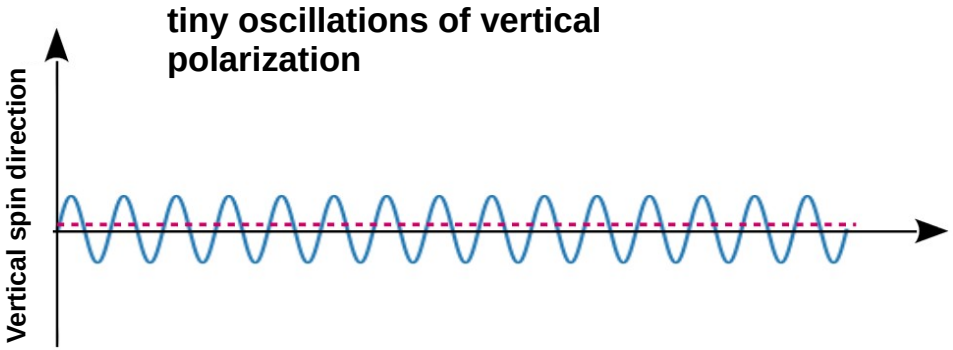
access to EDM

RF WIEN FILTER

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

⇩

no accumulation of vertical asymmetry

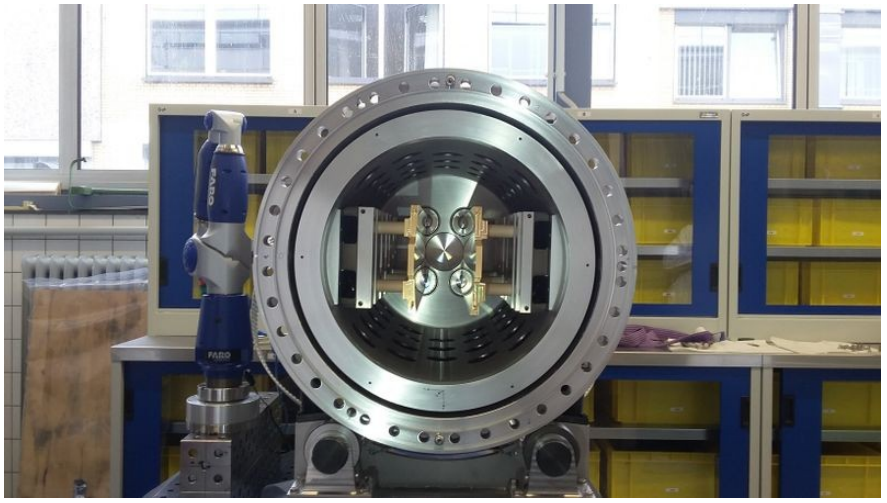


RF Wien filter

*Heberling, Hölscher and **J. Slim***

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

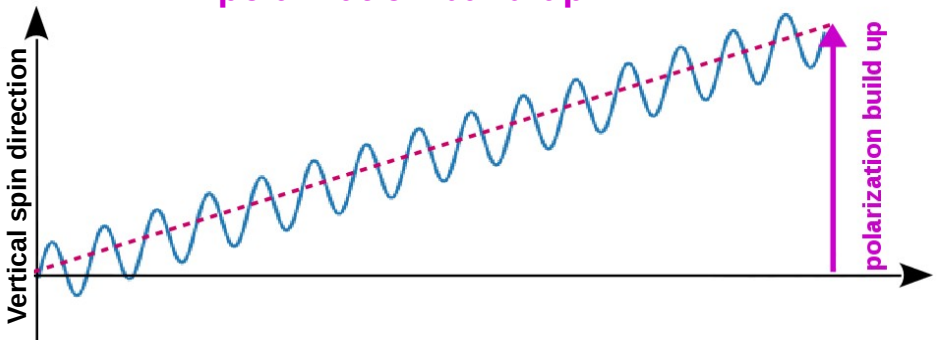
- Lorentz force $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0$
- $\vec{B} = (0, B_y, 0)$ And $\vec{E} = (E_x, 0, 0)$
- provides $\vec{E} \times \vec{B}$ by design



phase lock between spin precession and RF Wien filter

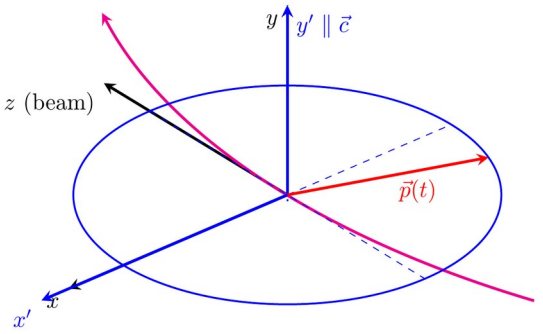
⇩

polarization build-up

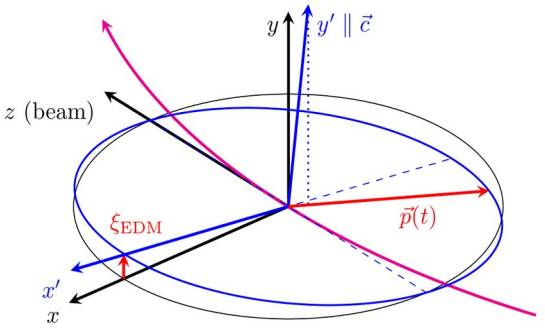


EFFECT ON INVARIANT SPIN AXIS

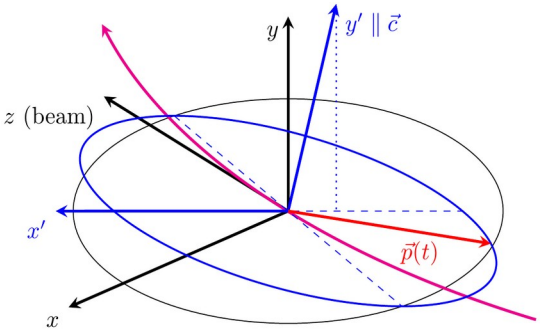
EDM absent



Pure EDM effect

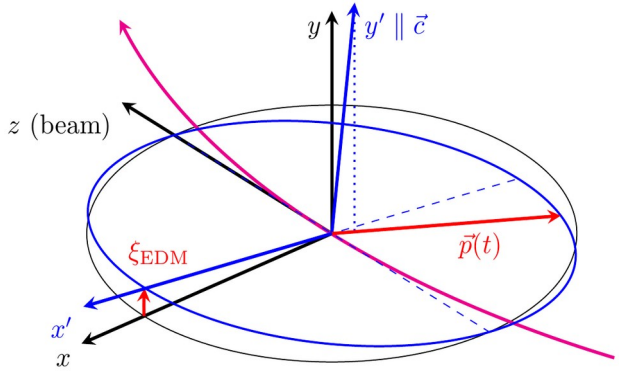


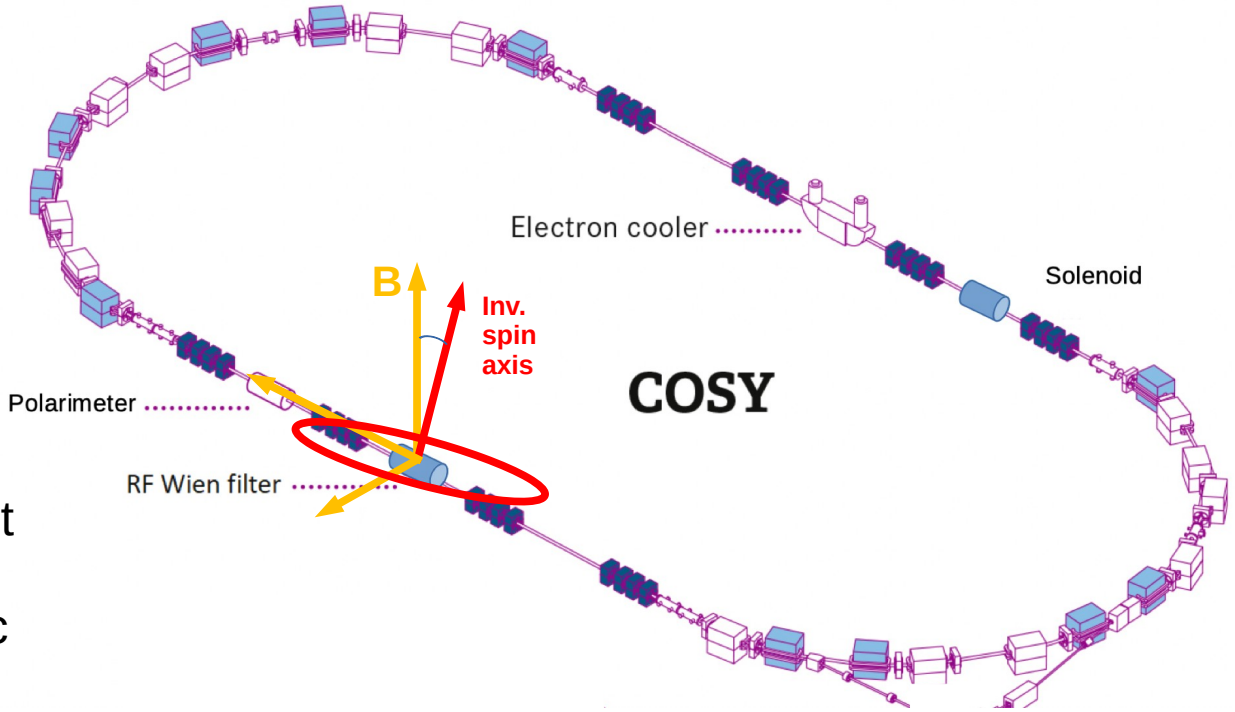
EDM + magnetic misalignments



MEASUREMENT OF THE EDM EFFECT

How the EDM effect actually measured:

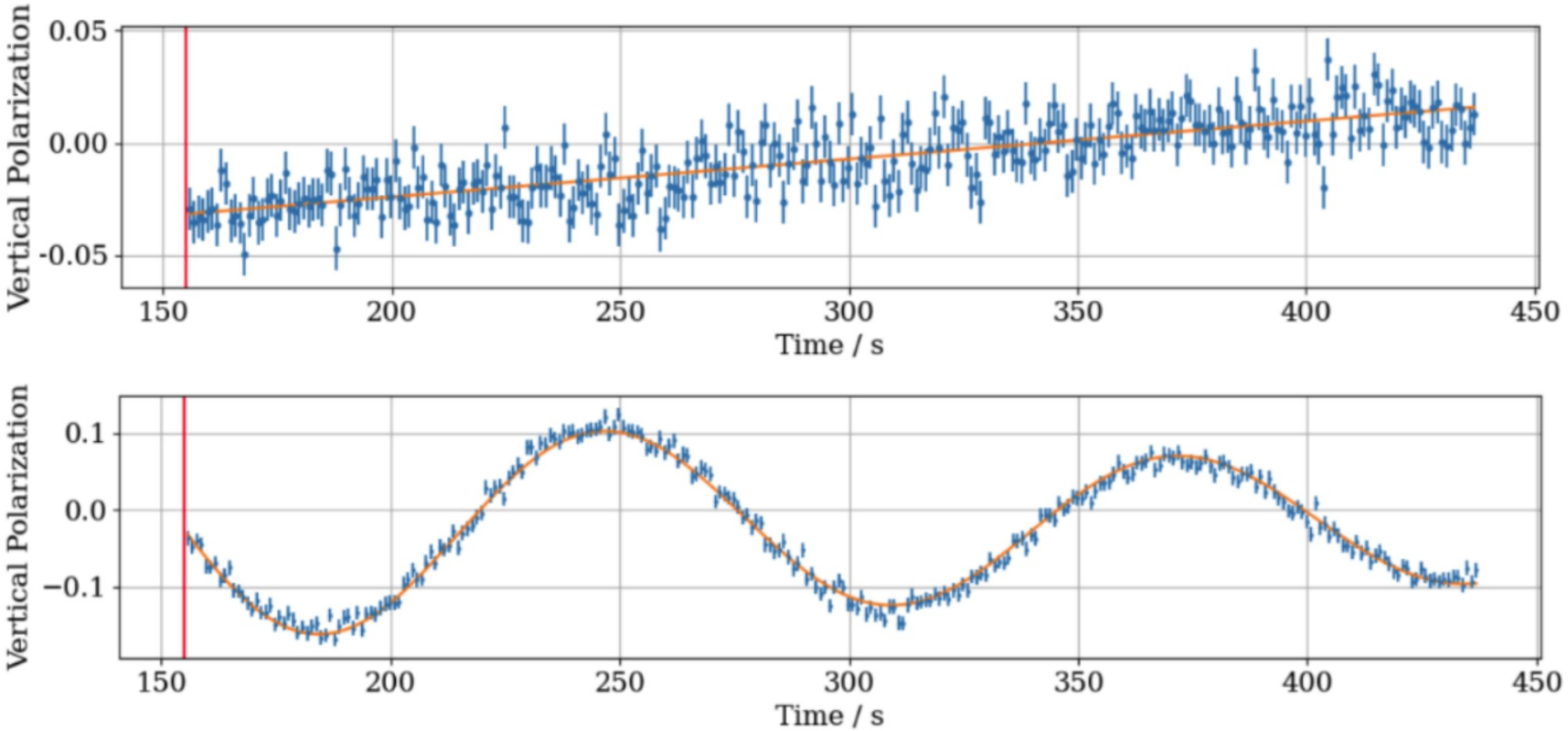




- The RF Wien filter is rotated about beam axis:
  - it generates radial magnetic field, which allows to compensate to radial tilt of invariant spin axis
- Solenoid introduces longitudinal magnetic field:
  - It change the invariant spin axis direction longitudinally

MEASUREMENT OF THE EDM RESONANCE STRENGTH

- No oscillations in pilot bunch → **used for phase-lock.**
- Determine oscillation frequencies Ω^{py}
- Wien filter map to determine invariant spin axis.



RESONANCE STRENGTH MAP

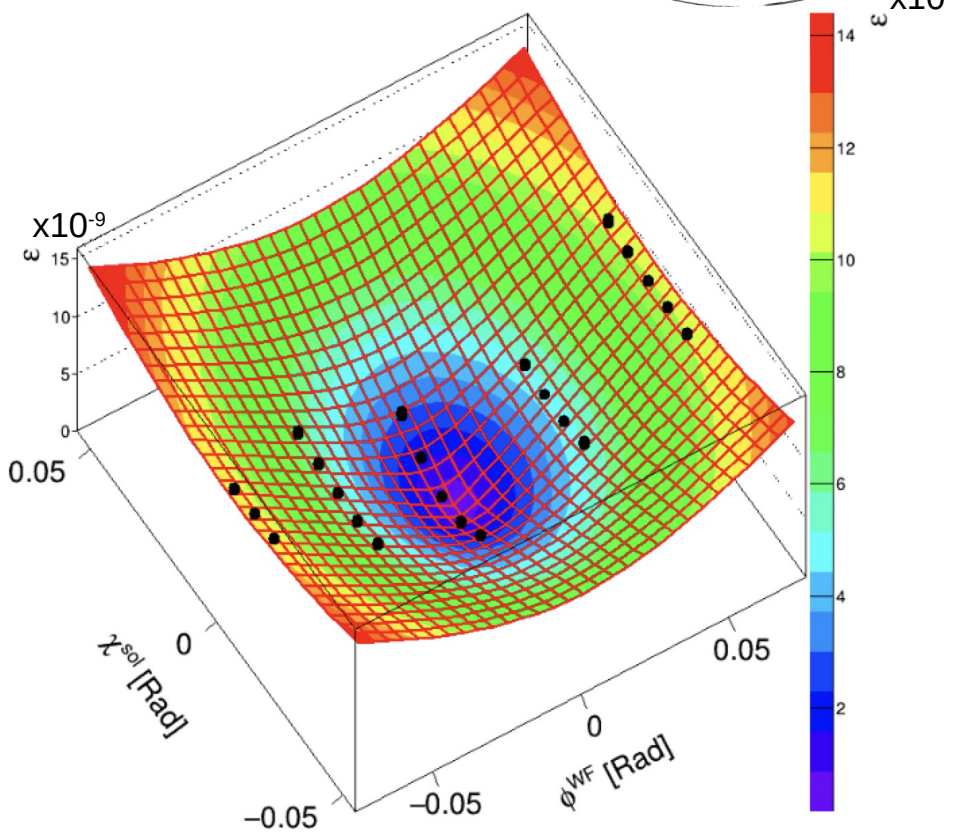
EDM resonance strength defined as ratio of angular frequency Ω^{p_y} to orbital angular frequency Ω^{rev}

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

Two simultaneously applied spin rotations, one in each opposite straight section:

1. RF Wien filter magnetic axis rotated by small angle → generates radial magnetic RF field about which spins precess.
2. Magnetic field of Siberian snake opposite to Wien filter → provides longitudinal tilt of invariant spin axis.

Minimum of the surface shows orientation of invariant spin axis



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

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