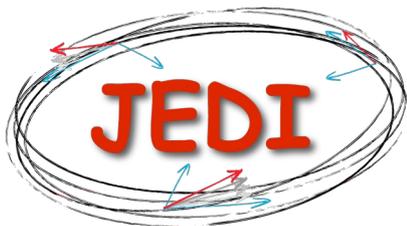


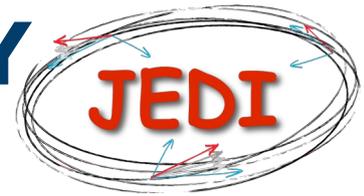
THE SEARCH FOR ELECTRIC DIPOLE MOMENT OF CHARGED PARTICLES USING STORAGE RING COSY

PSTP'22 MAINZ 30.09.2022 VERA SHMAKOVA FOR THE JEDI COLLABORATION



**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)

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

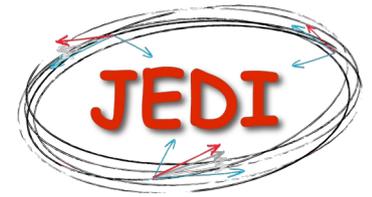
- Preference of matter (A. Sakharov criteria, 1967)

CP violation

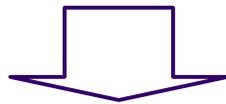


- CP violation in SM is not sufficient

ELECTRIC DIPOLE MOMENT

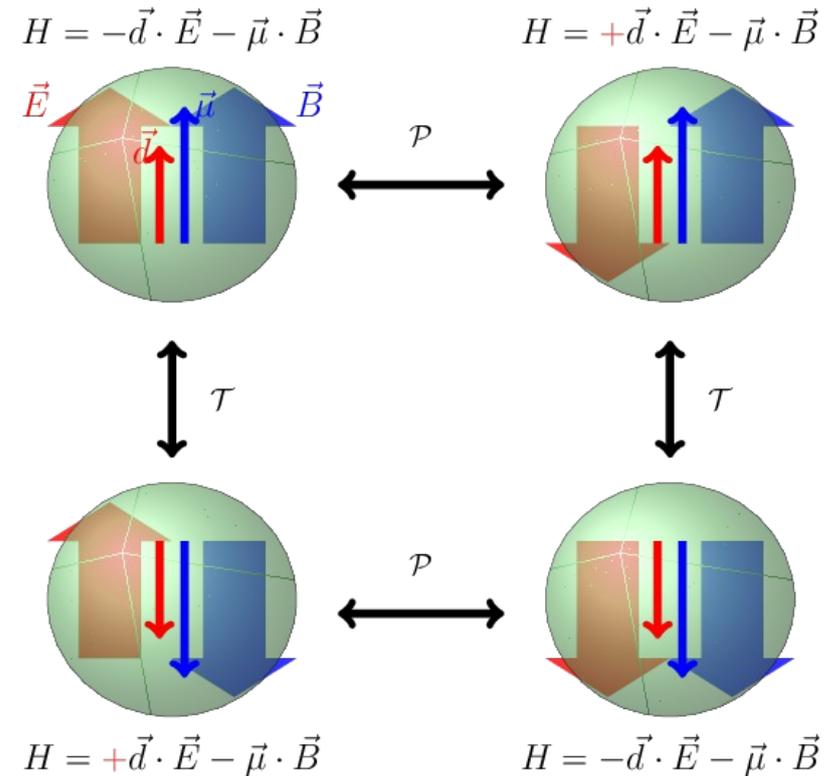


- EDM violates both T, P symmetries

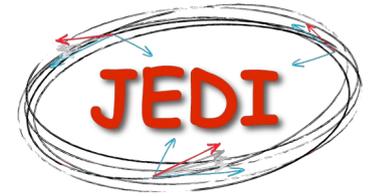


- EDM violates CP symmetry (if CPT conserved)

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



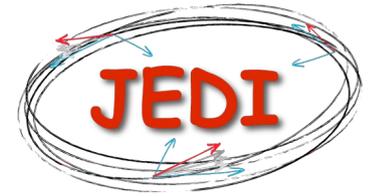
EDM AT STORAGE RINGS



THOMAS - BMT EQUATION:

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

EDM AT STORAGE RINGS



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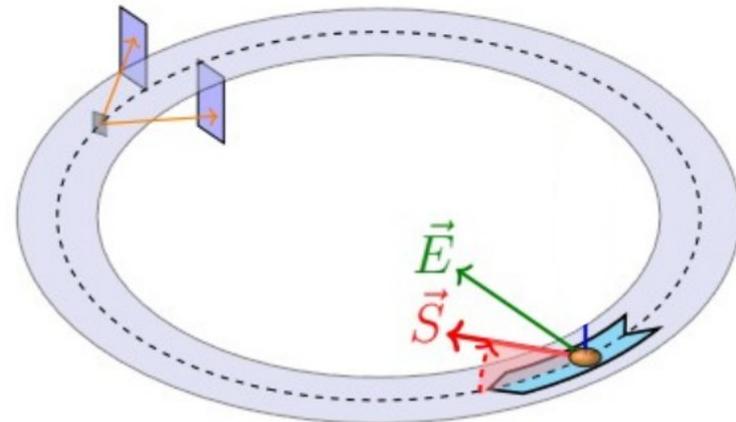
$$\vec{\Omega}_{EDM} = -\frac{\eta q}{2mc} \left\{ \vec{E} + c\vec{\beta} \times \vec{B} \right\}$$

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

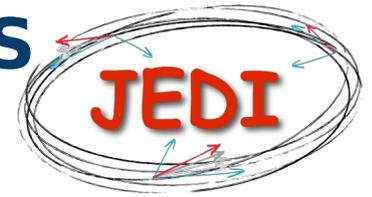
In case of purely electric ring:

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

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



EDM FOR CHARGED PARTICLE IN 3 STAGES



PRESTO

Stage 1

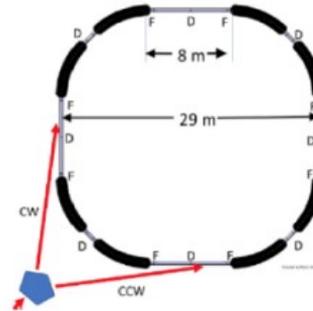
- precursor experiment



pure magnetic ring

Stage 2

- prototype ring



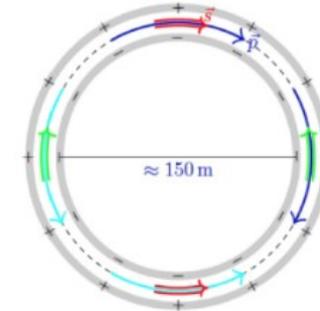
combined E/B ring

simultaneous CW-CCW beams

frozen spin

Stage 3

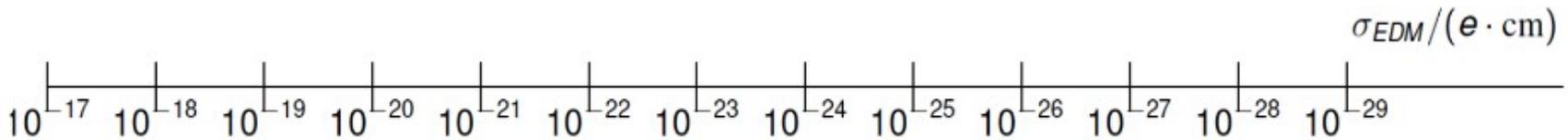
- dedicated storage ring



all electric proton ring

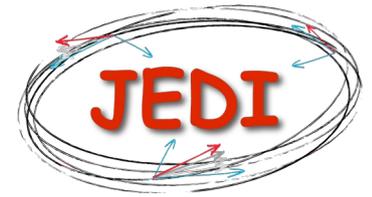
simultaneous CW-CCW beams

frozen spin



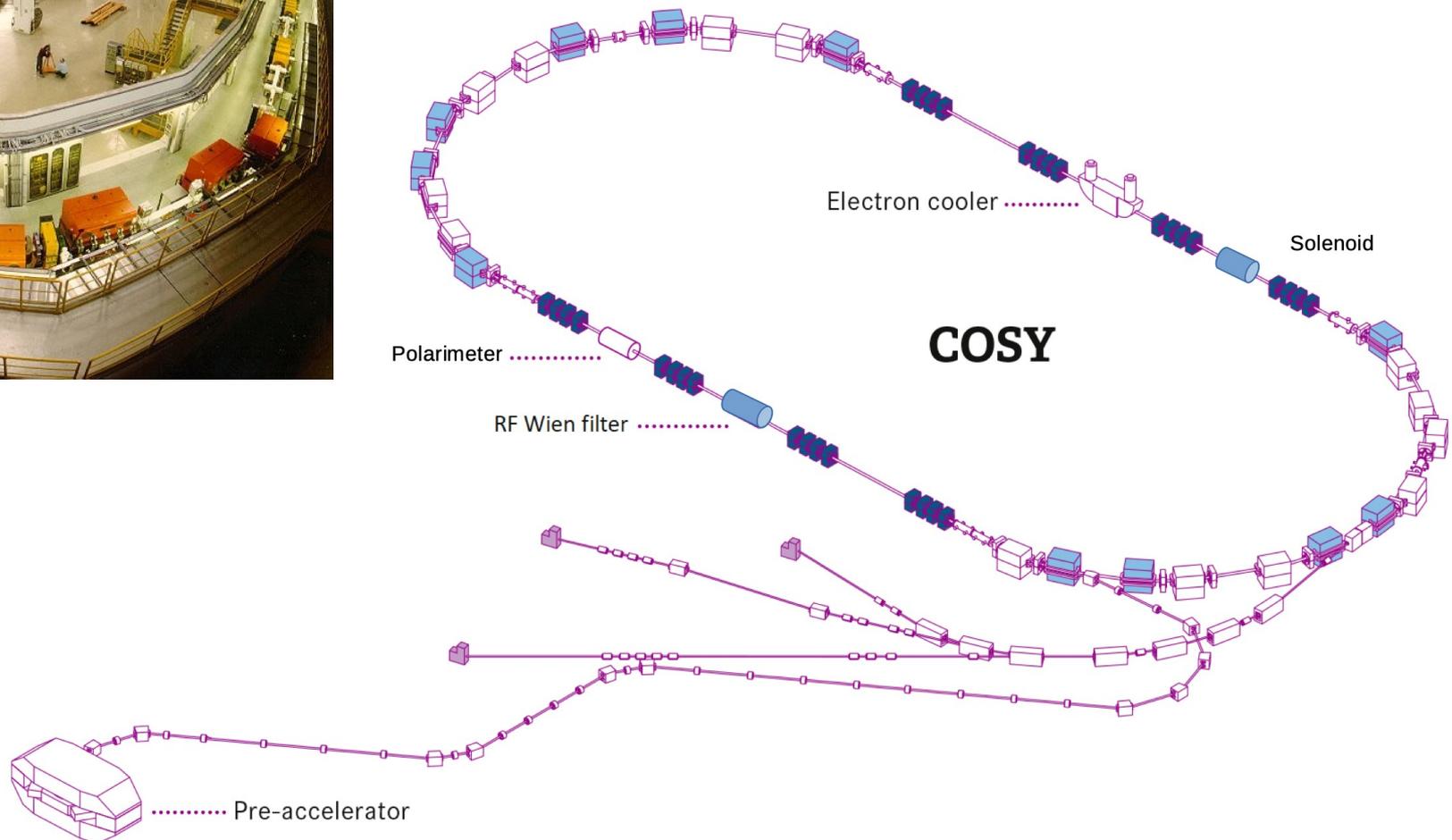
* F. Abusaif et al., "Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study," 2019. <https://arxiv.org/abs/1912.07881>

PRECURSOR EXPERIMENT AT COSY

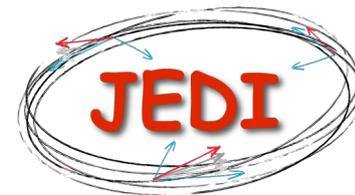


COoler SYnchrotron COSY:

- magnetic storage ring
- polarized protons and deuterons
- momenta $p = 0.3 - 3.7 \text{ GeV}/c$
- starting point for EDM measurement



EDM AT MAGNETIC RING



THOMAS - BMT EQUATION:

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

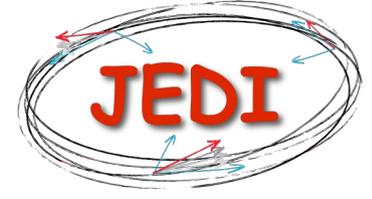
MDM causes fast spin precession in horizontal plane

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



access to EDM

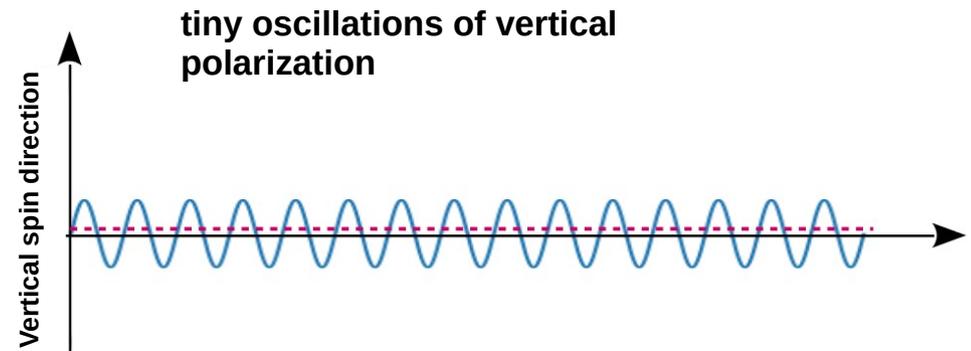
RF WIEN FILTER



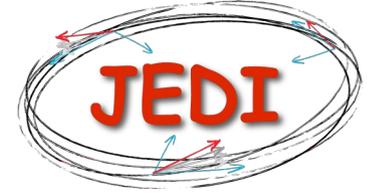
In the magnetic ring

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

\downarrow
no accumulation of vertical asymmetry

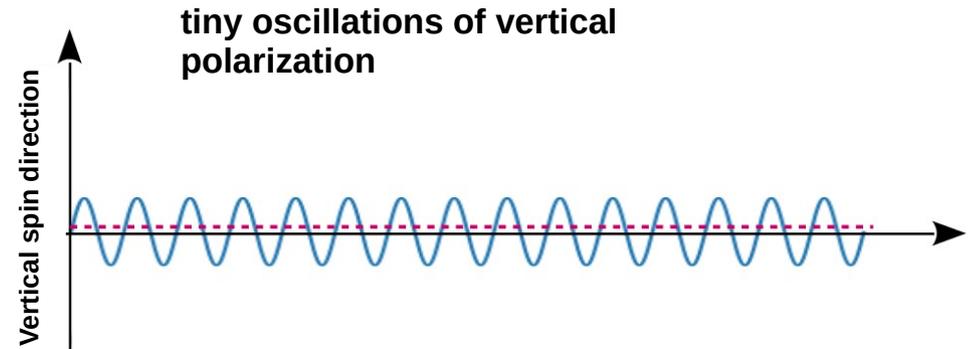


RF WIEN FILTER



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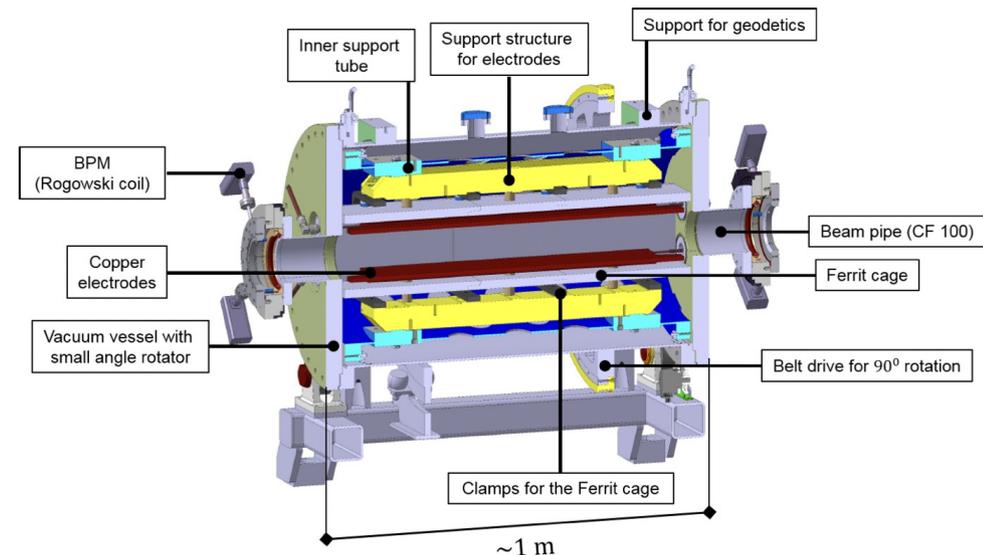
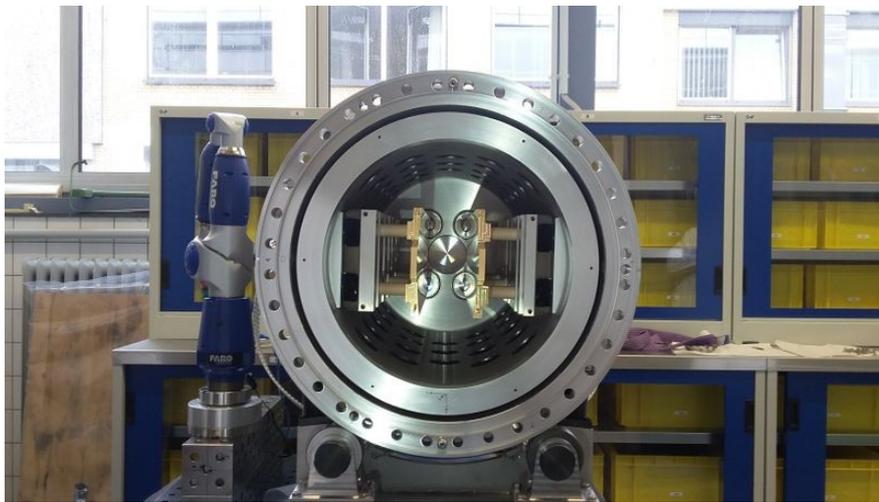


RF Wien filter

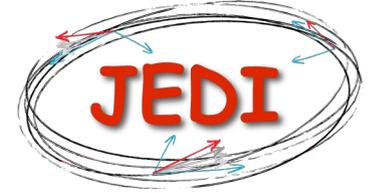
Heberling, Höscher and J. Slim

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 $\vec{E} = (E_x, 0, 0)$



RF WIEN FILTER

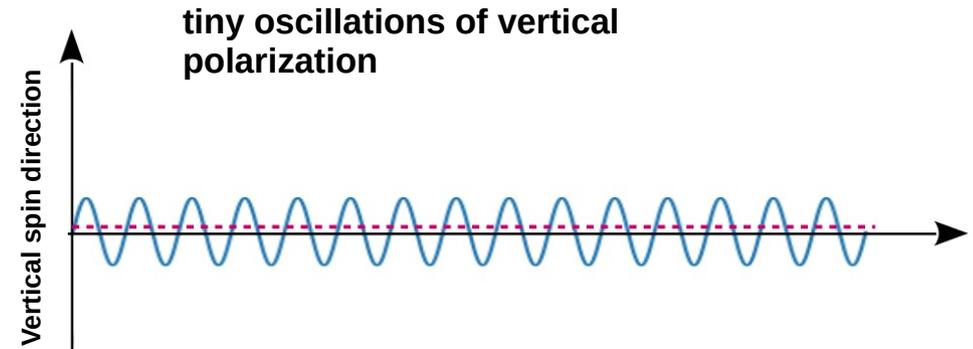


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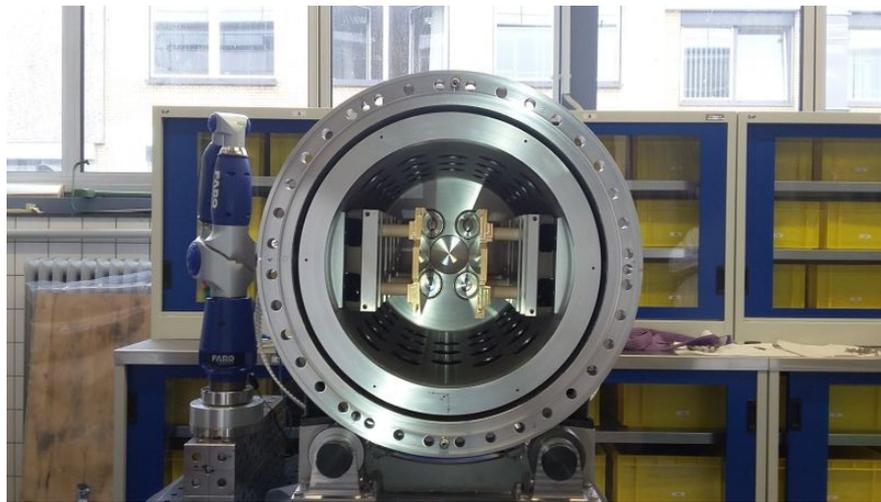


RF Wien filter

Heberling, Höscher and J. Slim

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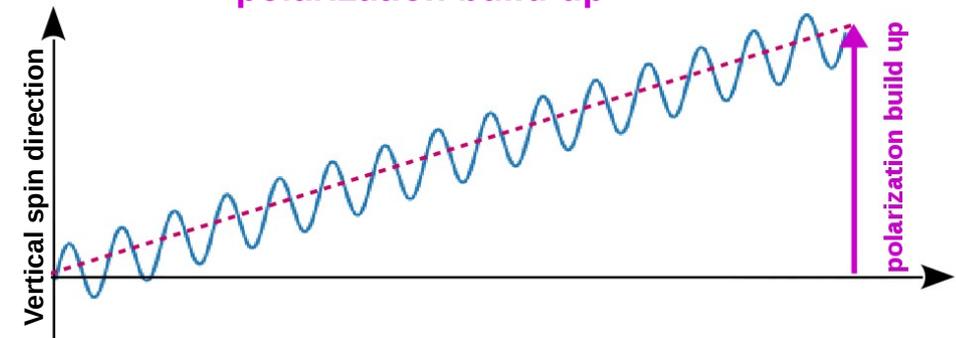
- Lorentz force $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0$
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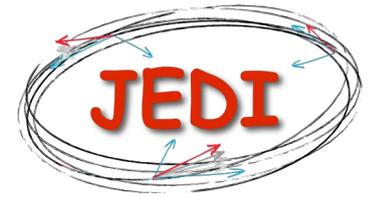
phase lock between spin precession and RF Wien filter



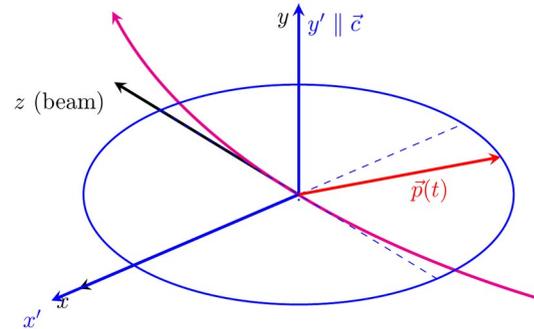
polarization build-up



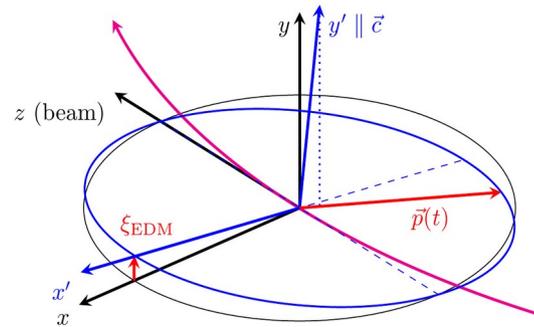
EFFECT ON INVARIANT SPIN AXIS



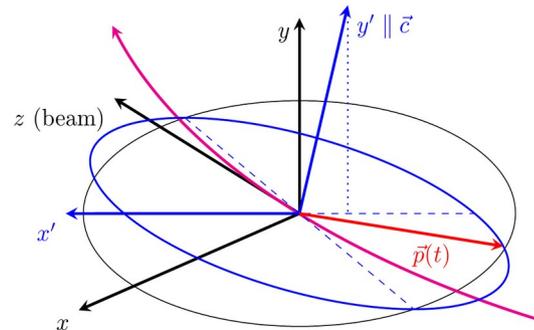
EDM absent



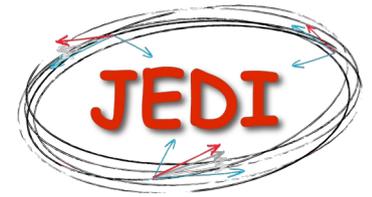
Pure EDM effect



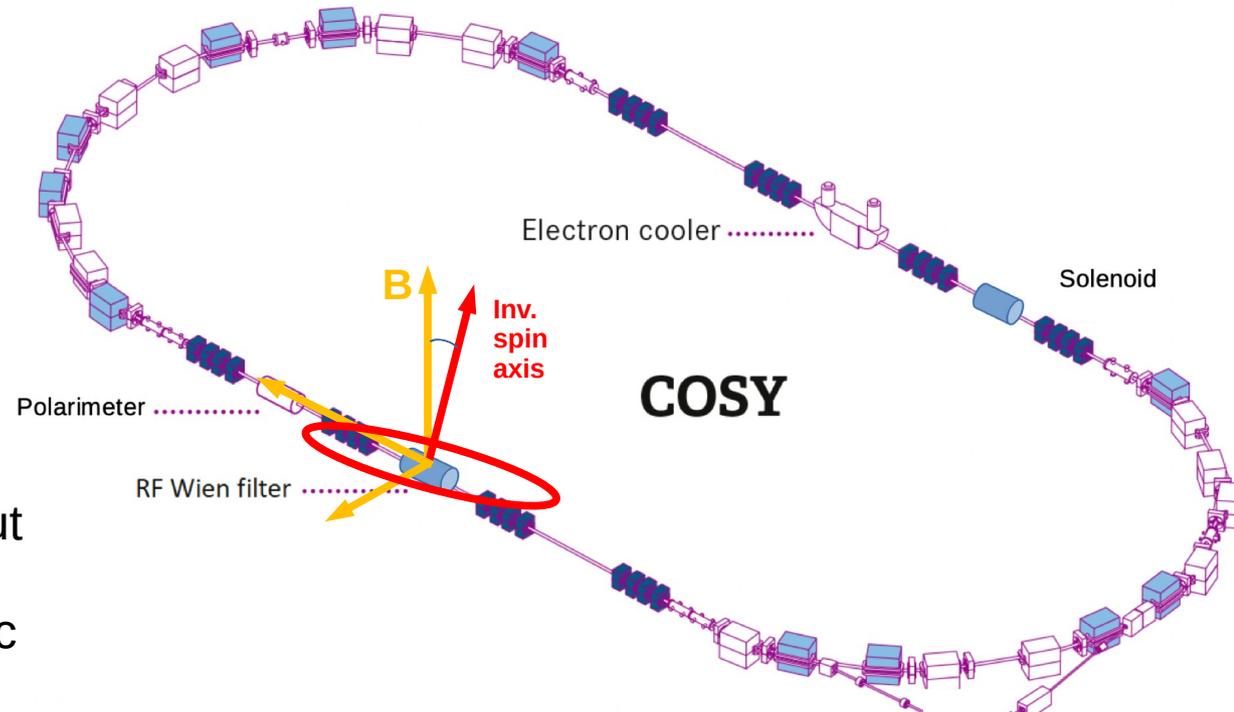
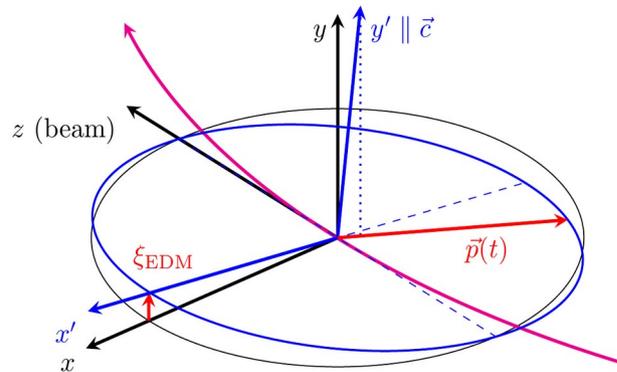
EDM + magnetic misalignments



MEASUREMENT OF THE EDM EFFECT

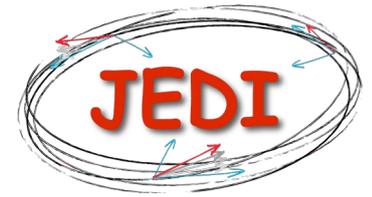


How the EDM effect actually measured:

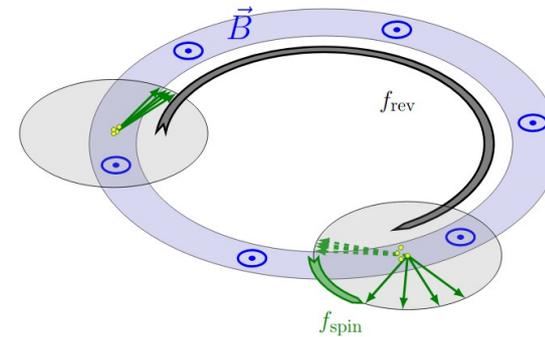


- The RF Wien filter is rotated about beam axis:
 - it generates radial magnetic field, which allows to compensate to radial tilt of invariant spin axis
- Solenoid introduces longitudinal magnetic field:
 - It change the invariant spin axis direction longitudinally

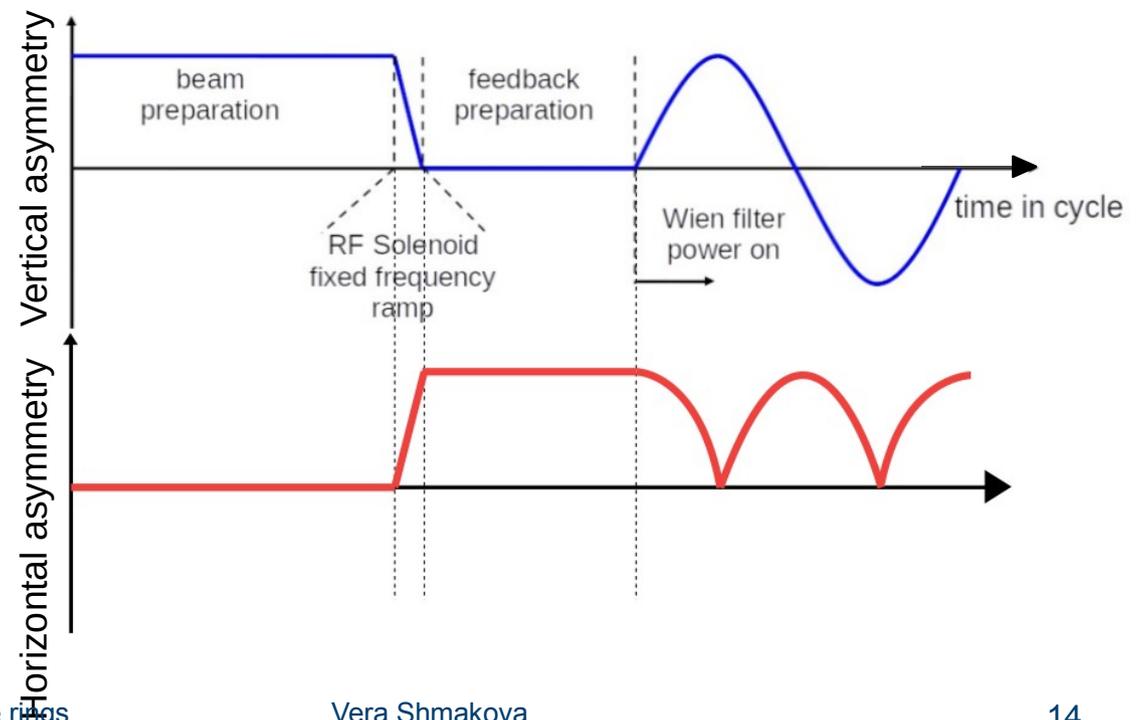
PRINCIPLE OF MEASUREMENTS



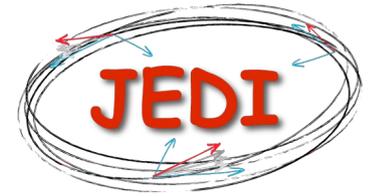
- Coherent ensembles in ring plane \rightarrow spin coherence time has to be longer than a measurement
- SCT > 1000 s.



Feedback: the basic workflow:

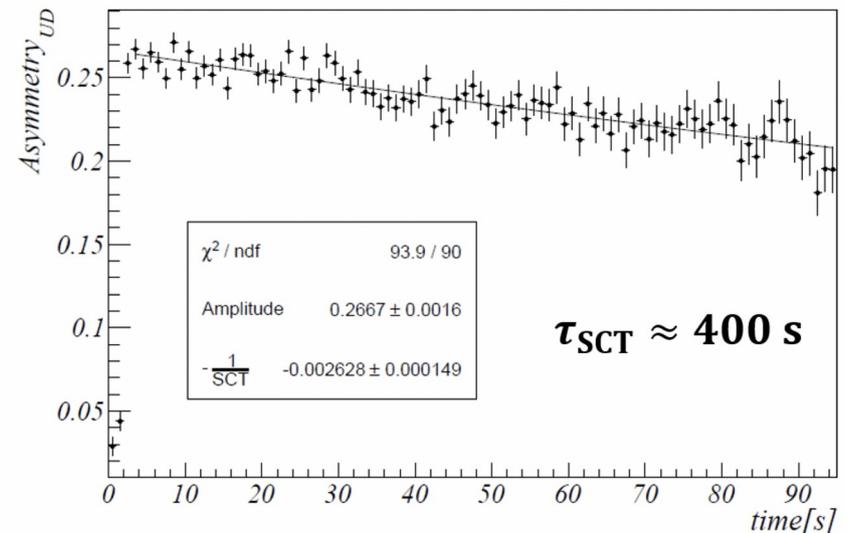
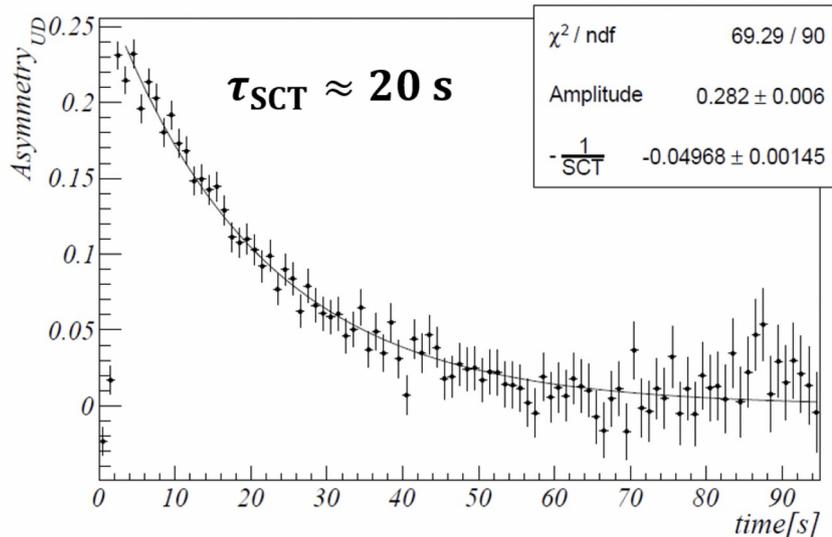
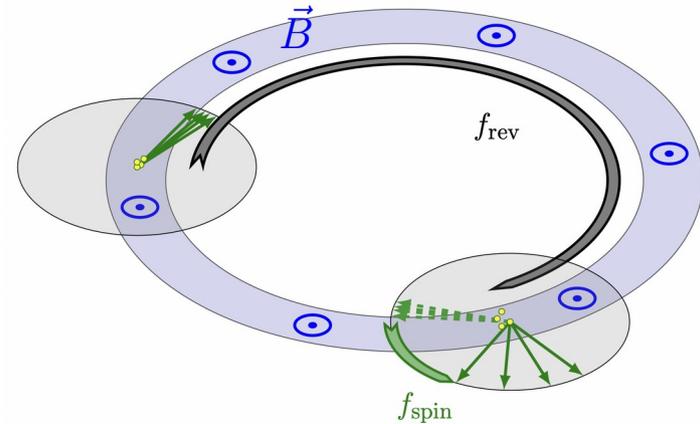


SPIN COHERENCE TIME

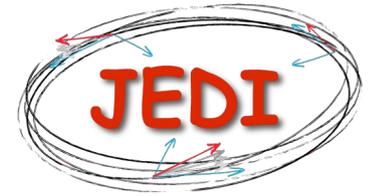


For long SCT:

- Beam bunching
- Cooling
- Correction with sextupole magnets

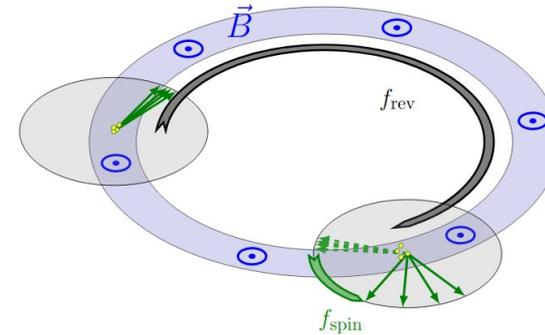


PRINCIPLE OF MEASUREMENTS

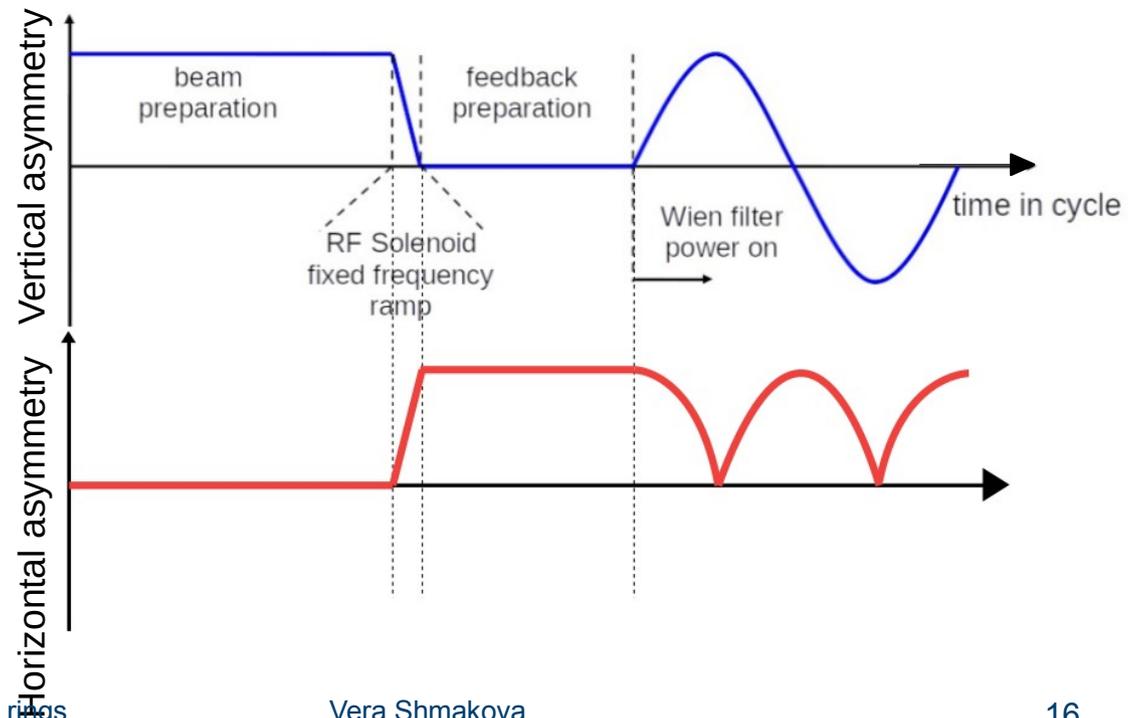


- Coherent ensembles in ring plane → spin coherence time has to be longer than a measurement
- SCT > 1000 s.
- Spin precesses with 120 kHz.
- Wien filter operates on resonance:

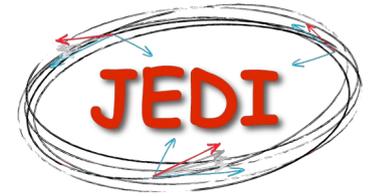
$$f = f_{\text{COSY}} + f_{\text{spin pres}} = 871.430 \text{ kHz}$$
- Phase lock between spin precession and Wien filter



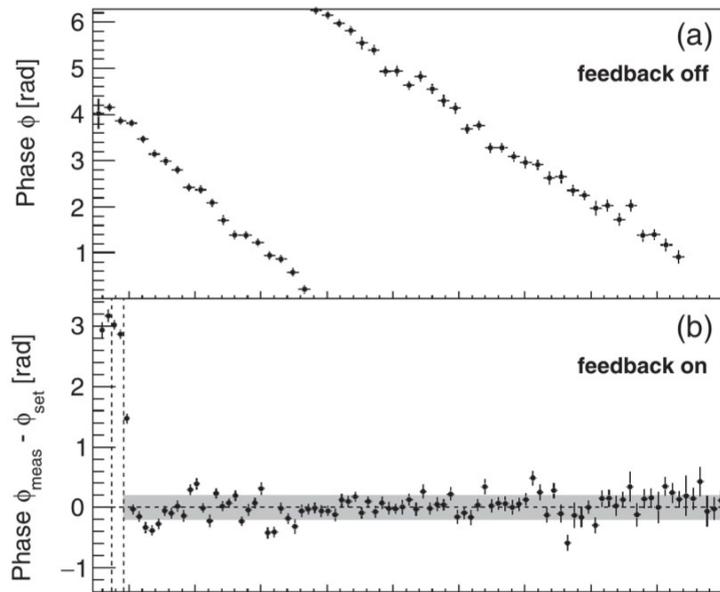
Feedback: the basic workflow:



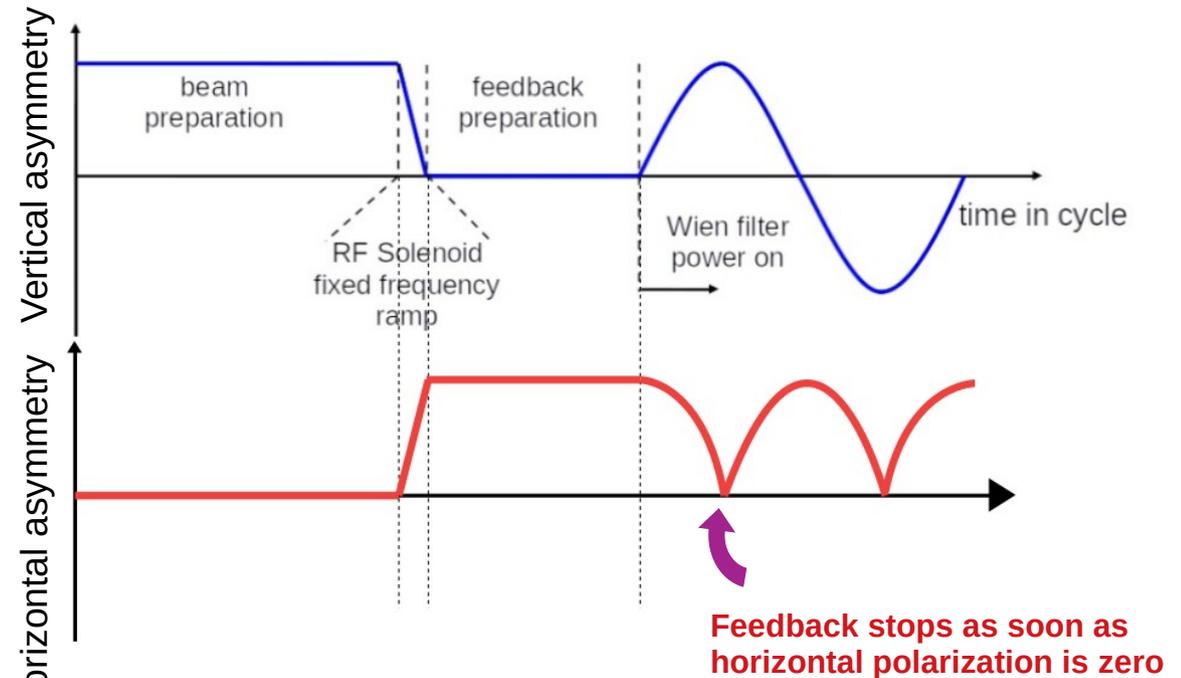
PRINCIPLE OF MEASUREMENTS



- 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

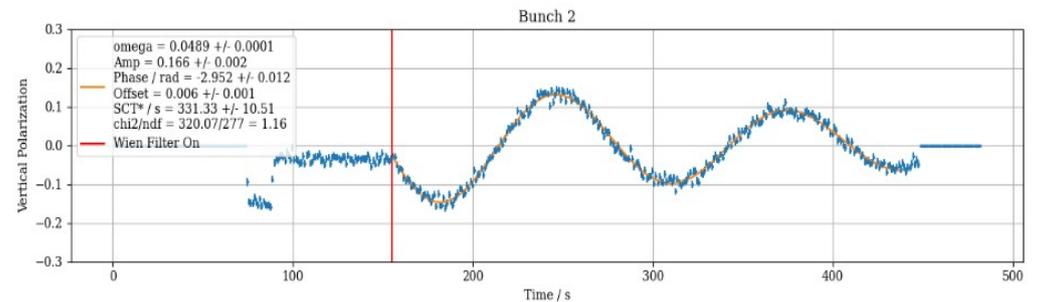
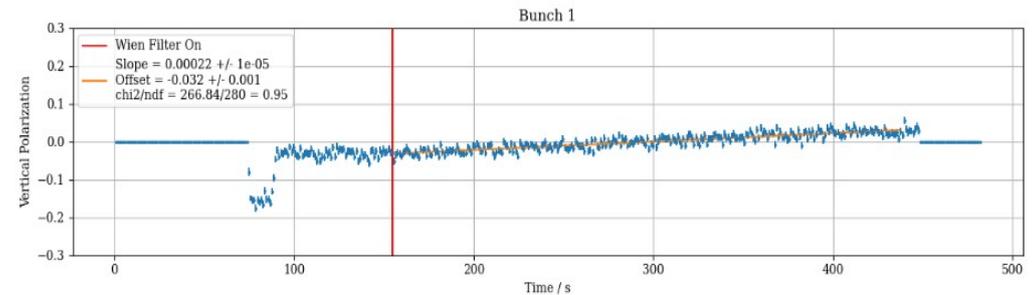
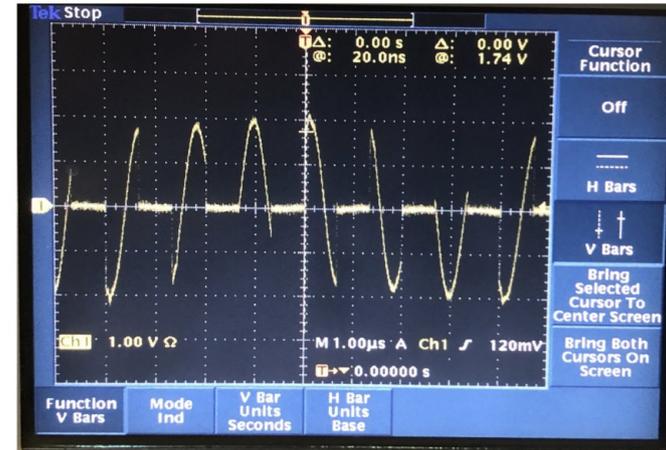
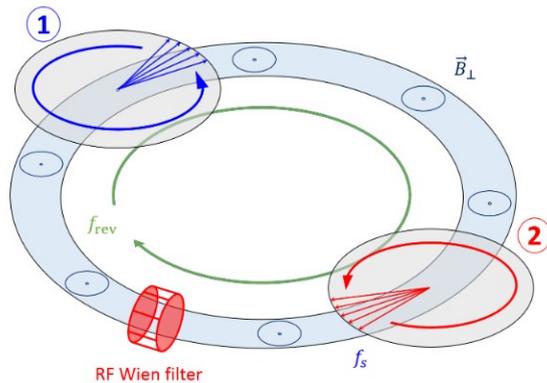


RF SWITCHES

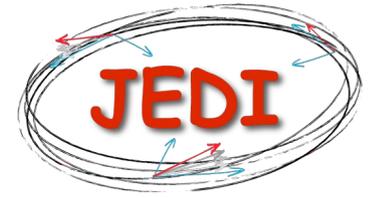


Rotating the spin of one bunch out of the two in the ring:

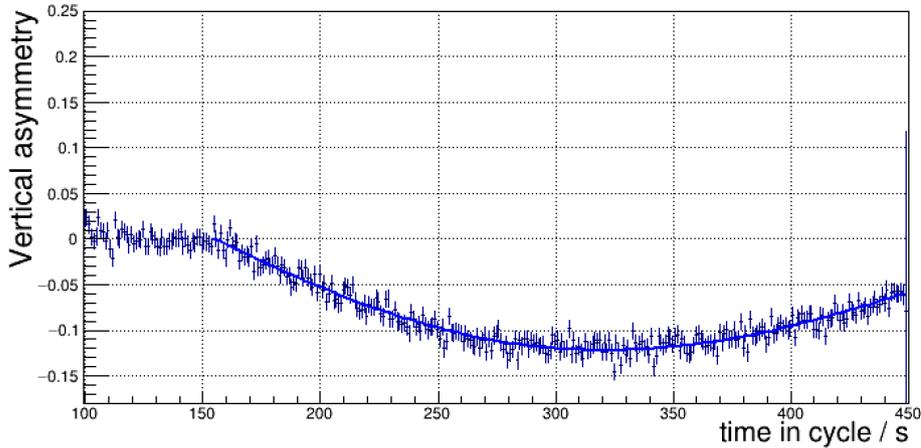
- 8 high-speed RF switches to gate the WF power for one of two bunches
- Capable of short switch time \sim few ns
- Bunch ② feels the power and oscillate
- Bunch ① is used as pilot bunch for phase locking



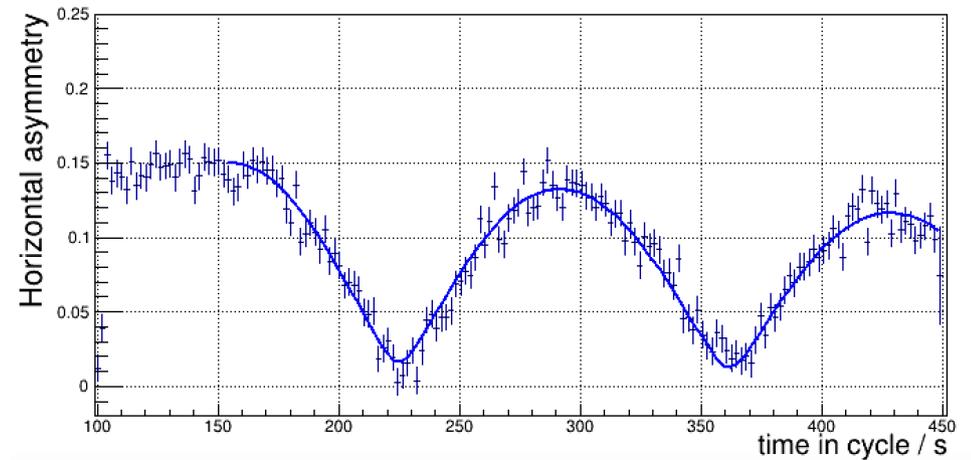
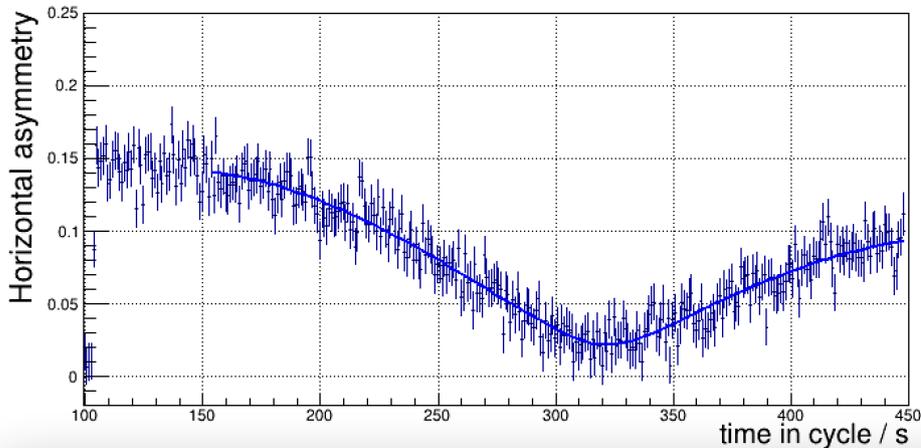
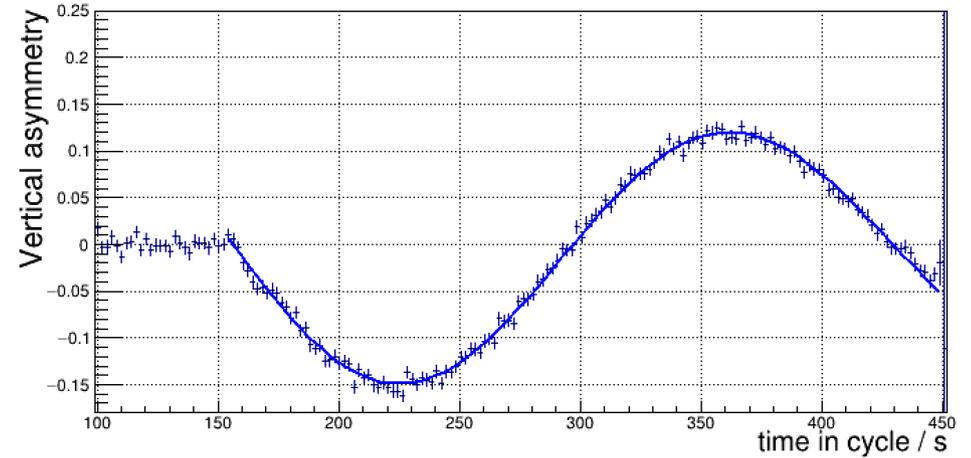
POLARIZATION OUT-OF PLANE OSCILLATION



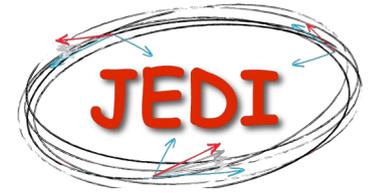
WF @ 0
Solenoid @ -4 A



WF @ 2 Deg
Solenoid @ 0 A



RESULTS



Parametric resonance strength defined as:

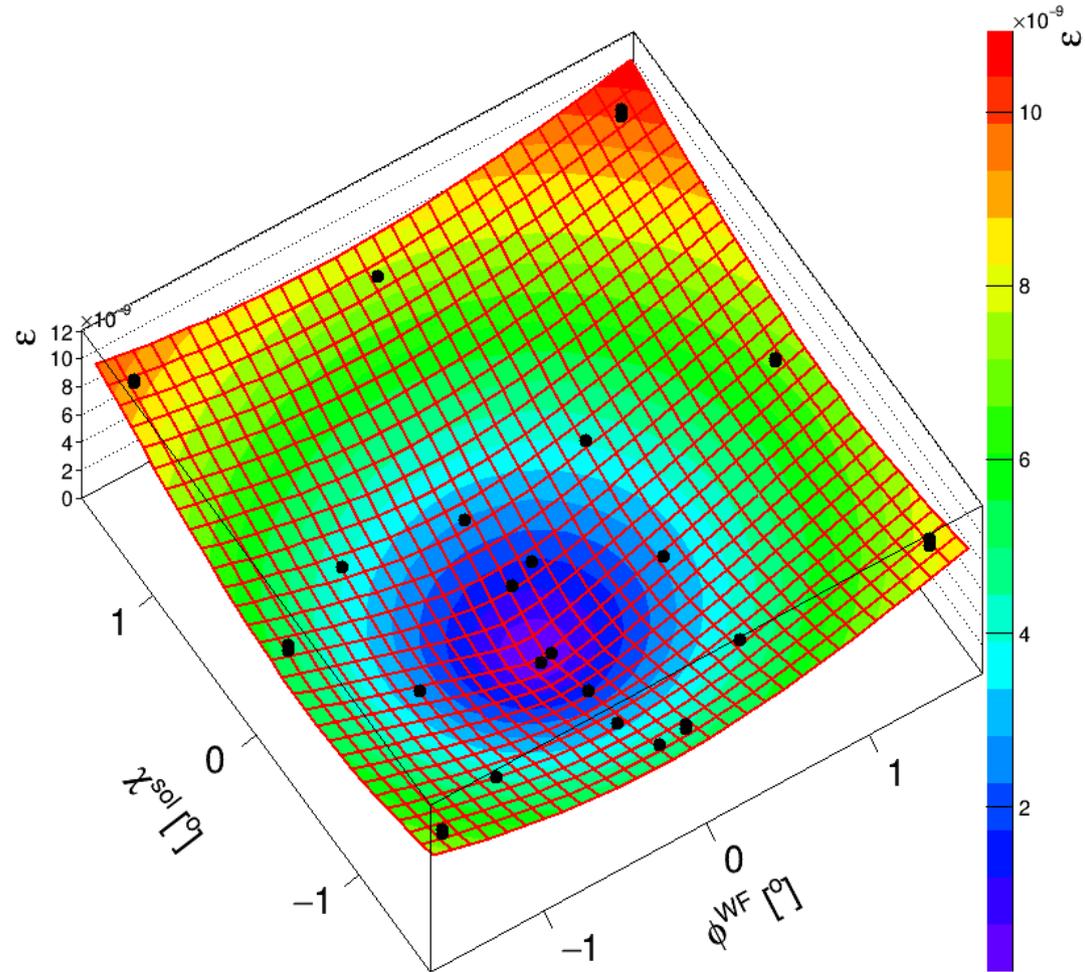
$$\varepsilon^{EDM} = \frac{\Omega^{P_y}}{\Omega^{rev}}$$

Minimum of the surface shows orientation of invariant spin axis:

$$\varphi_0^{wf} = 3.42 \pm 0.06 \text{ mrad}$$

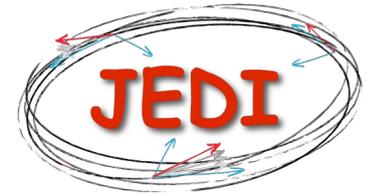
$$\chi_0^{sol} = 5.26 \pm 0.04 \text{ mrad}$$

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



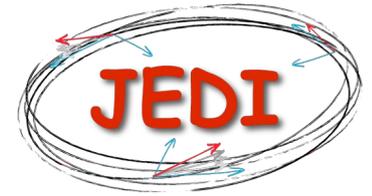
$$\varepsilon = \frac{\chi_{WF}}{4\pi} \sqrt{\left(A_{WF}^2 (\phi_0^{WF} - \phi^{WF})^2 + A_{Sol}^2 \left(\frac{\chi_0^{sol}}{2 \sin(\pi \nu_s)} - \chi^{sol} \right)^2 \right) + \varepsilon_0}$$

SUMMARY



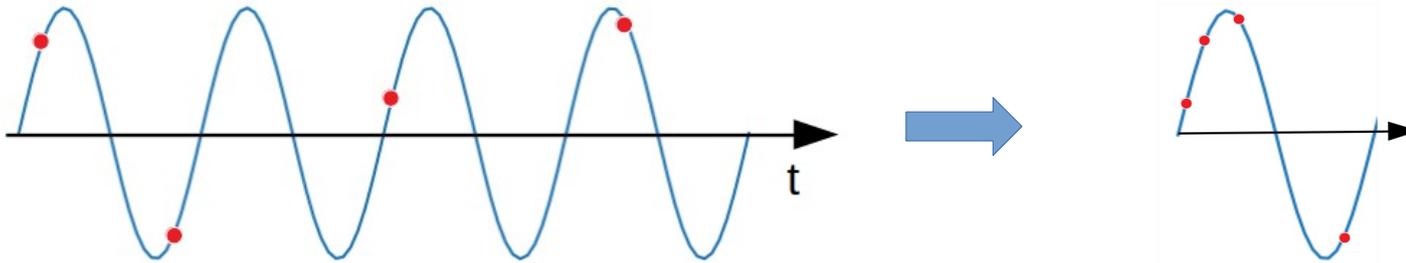
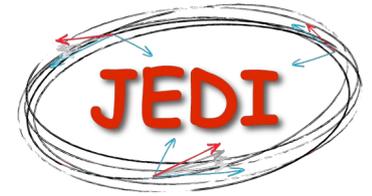
- Charged hadron EDMs: Possibility to find sources of CP violation and to explain matter-antimatter asymmetry in the universe.
- Precursor experiments performed as a proof-of-principle of EDM measurement at storage rings.
- New method of managing the polarization for one of two bunches in the ring was developed and performed
- CERN Yellow Report prepared by CPEDM collaboration
F. Abusaif et al., “Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study,” 2020 <https://arxiv.org/abs/1912.07881>
- Work on Design Report for PTR ongoing. Proposal **PRESTO** is out.
- COSY remains a unique facility for such studies.

LIST OF IMPROVEMENTS



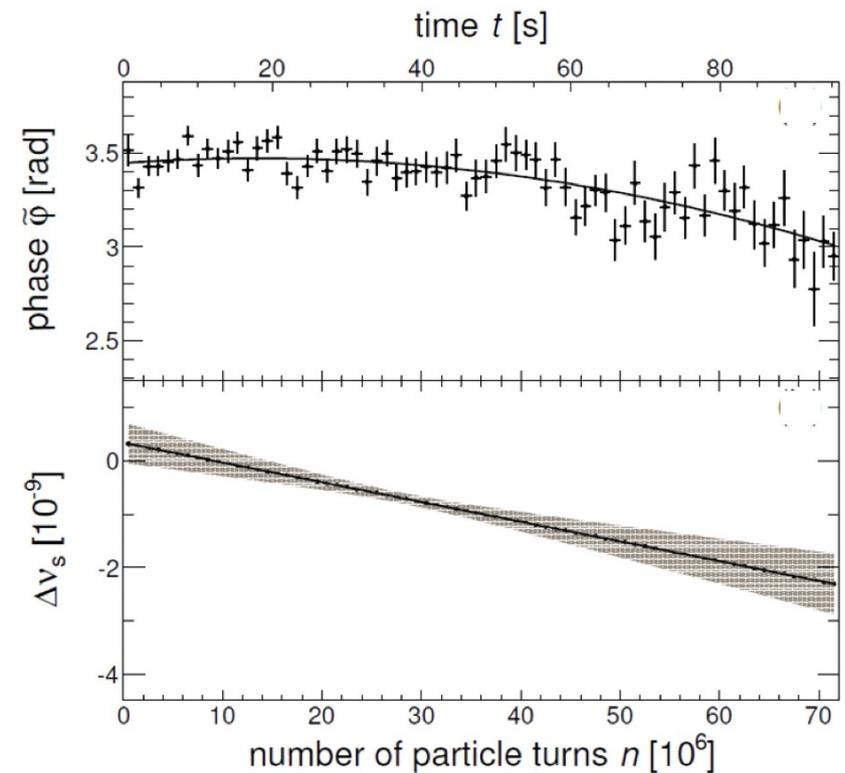
- Alignment campaigns of COSY magnet system
- Beam-based alignment
PhD thesis T. Wagner
- New tool for fast tune and chromaticity measurement
P. Niedermayer and B. Breitkeutz
- Slow control system
I. Bekman and IKP4
- COSY signals and distribution was improved
K. Laihem
- Rogowski coils at the Wien filter 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

SPINTUNE AND HORIZONTAL ASYMMETRY

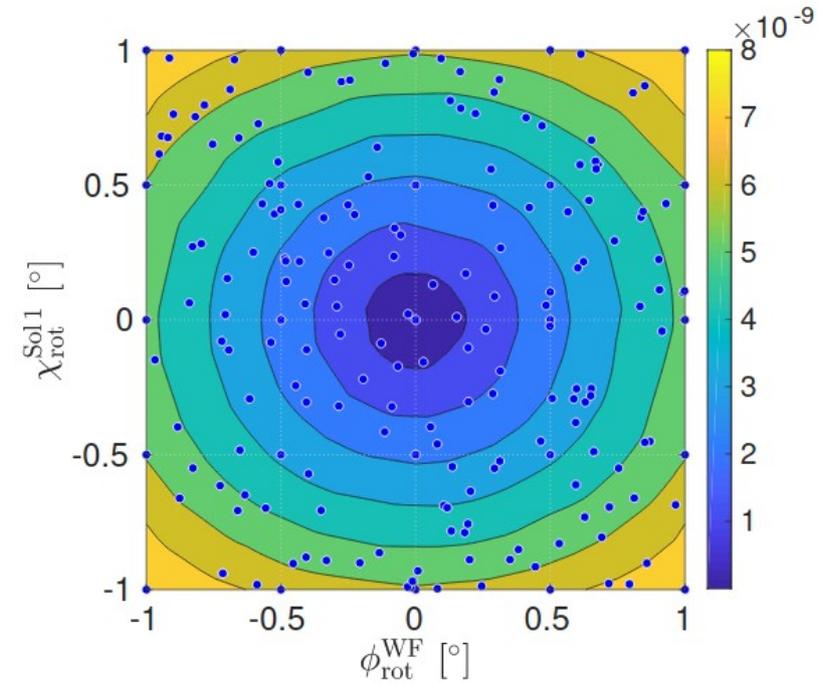
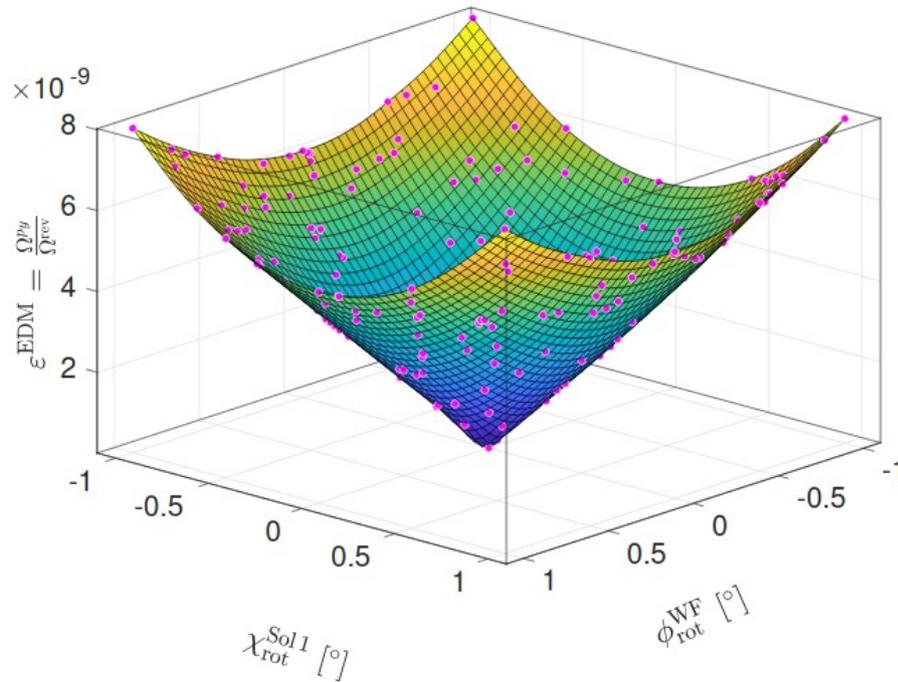
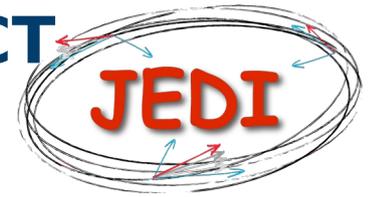


- Spin precesses with 120 kHz.
- With event rates of $\sim 15000 \text{ s}^{-1}$, there is 1 hit per 10 precessions.
- Not possible to resolve horizontal oscillation directly
- Spintune is determined in each time bin with monitoring phase of measured horizontal asymmetry with fixed spin tune:

$$\nu_s(n) = \nu_s^{fix} + \frac{1}{2\pi} \frac{d\phi}{dn} = \nu_s^{fix} + \Delta \nu_s(n)$$

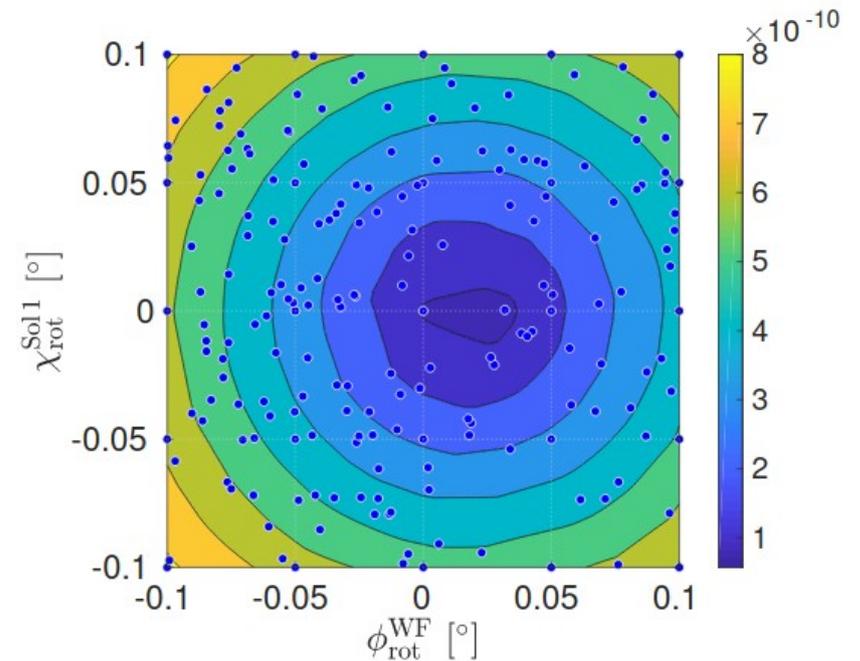
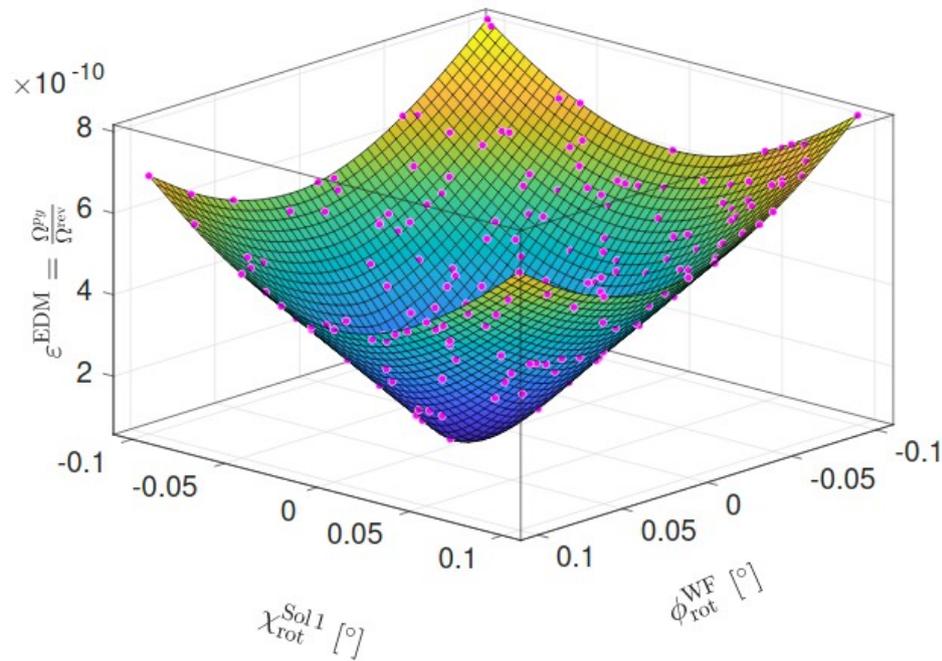
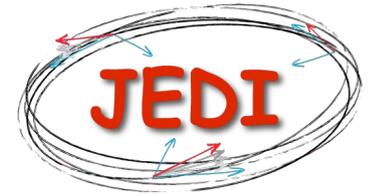


RESONANCE STRENGTH MAP W/O EDM EFFECT



EDM absent

RESONANCE STRENGTH MAP WITH EDM



$$d = 10^{-18} \text{ e cm}$$

JEPO POLARIMETER

