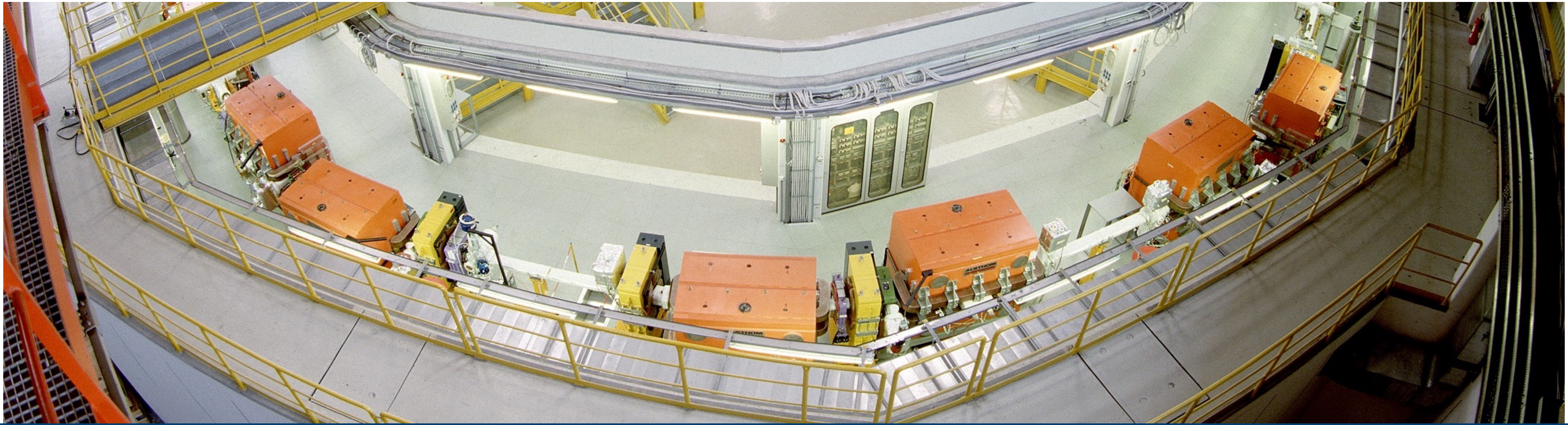


FIRST ELECTRIC DIPOLE MOMENT MEASUREMENT OF THE DEUTERON WITH THE WAVEGUIDE RF WIEN FILTER (SYSTEMATIC STUDIES)

23.02.2023 I ACHIM ANDRES (ON BEHALF OF JEDI)

JEDI

CBAC Meeting #14 (Proposal E005.8)

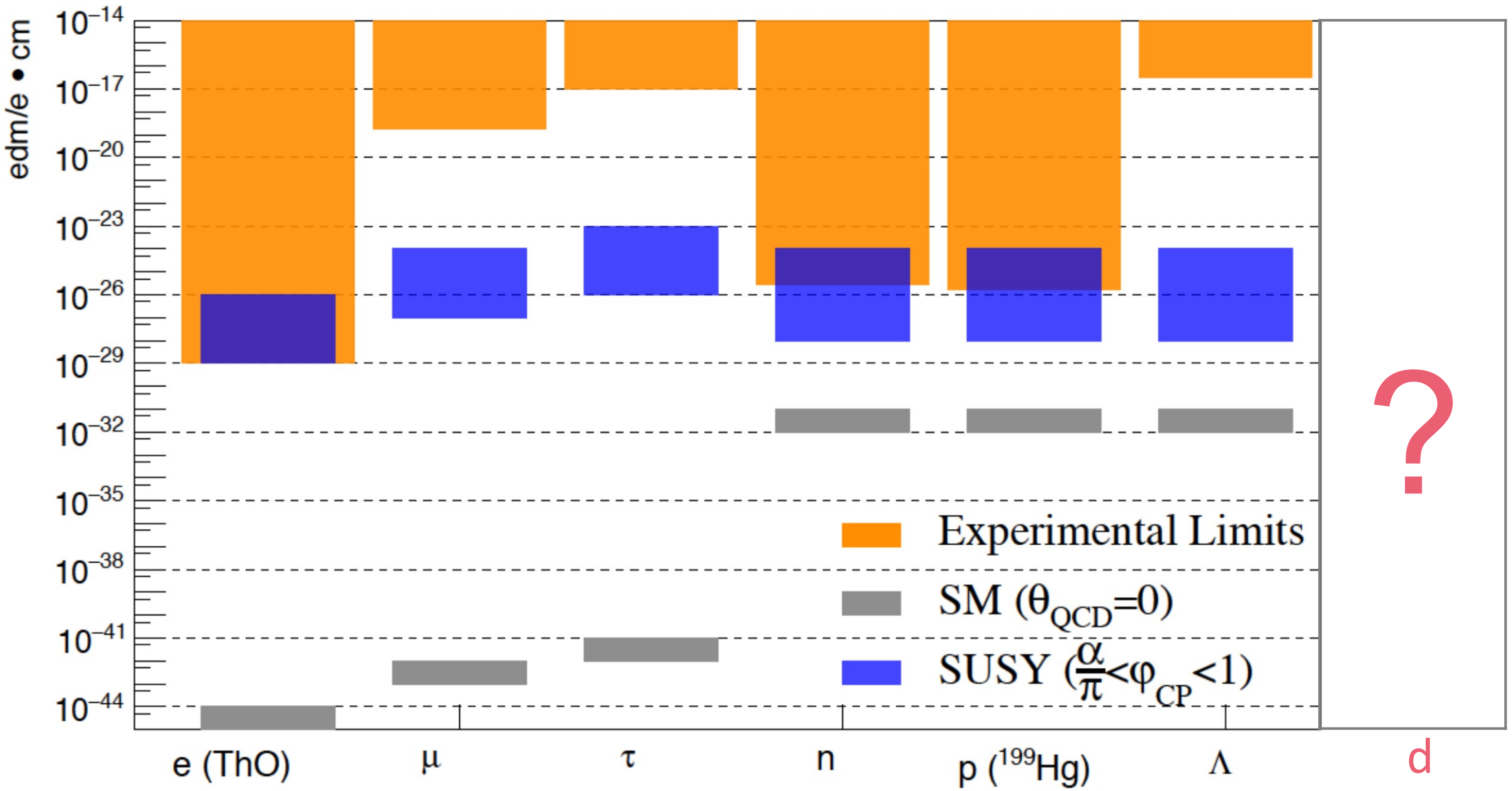
Physics Institute III B

RWTH AACHEN UNIVERSITY

JÜLICH Forschungszentrum

EDM LIMITS

JEDI Collaboration (2011) – Juelich Electric Dipole Moment Investigations



- According to A. Sakharov: **CP Violation** is needed
- EDMs of fundamental particles are CP violating
- EDM is a vectorial property aligned with the particles spin

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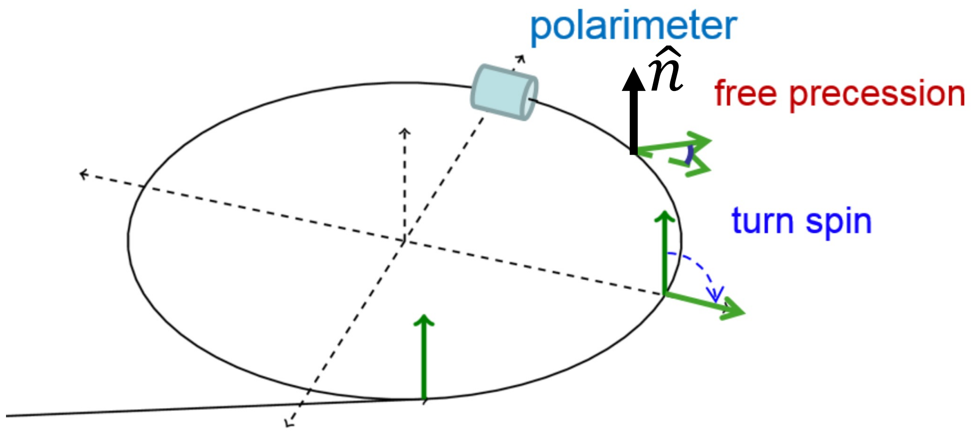
MEASUREMENT PRINCIPLE

- Measure **influence** of **EDM** on beam **polarization**
- **Injection** of vertically **polarized** deuteron beam
- **Rotate** polarization into **accelerator plane**
- COSY: **Magnetic** Ring → Polarization Vector **precesses** around invariant spin axis $\hat{n}$



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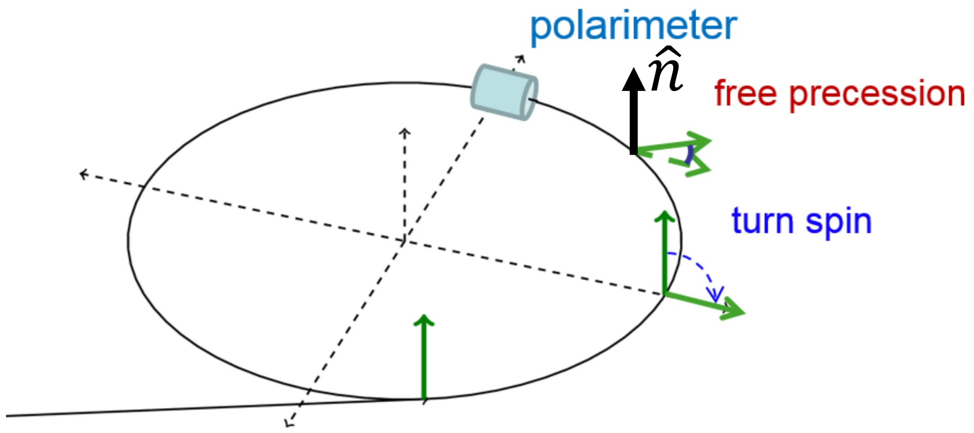
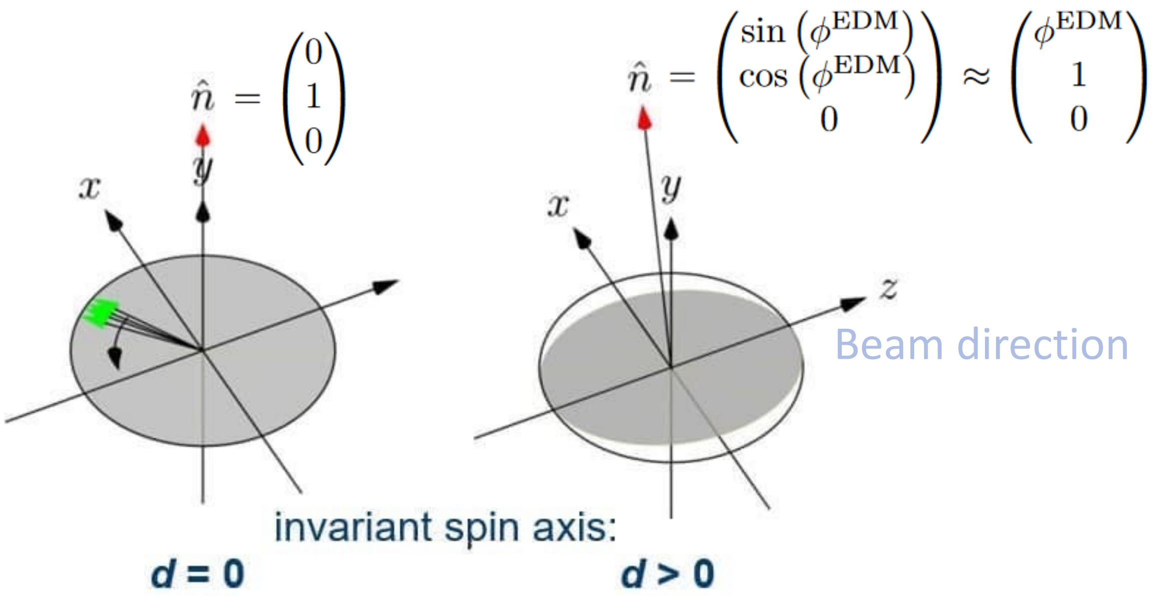
- Non-zero EDM: Tilts $\hat{n}$ in **radial** x direction by ϕ^{EDM} (no longitudinal effect expected)
- **Goal**: Determination of the **orientation** of $\hat{n}$





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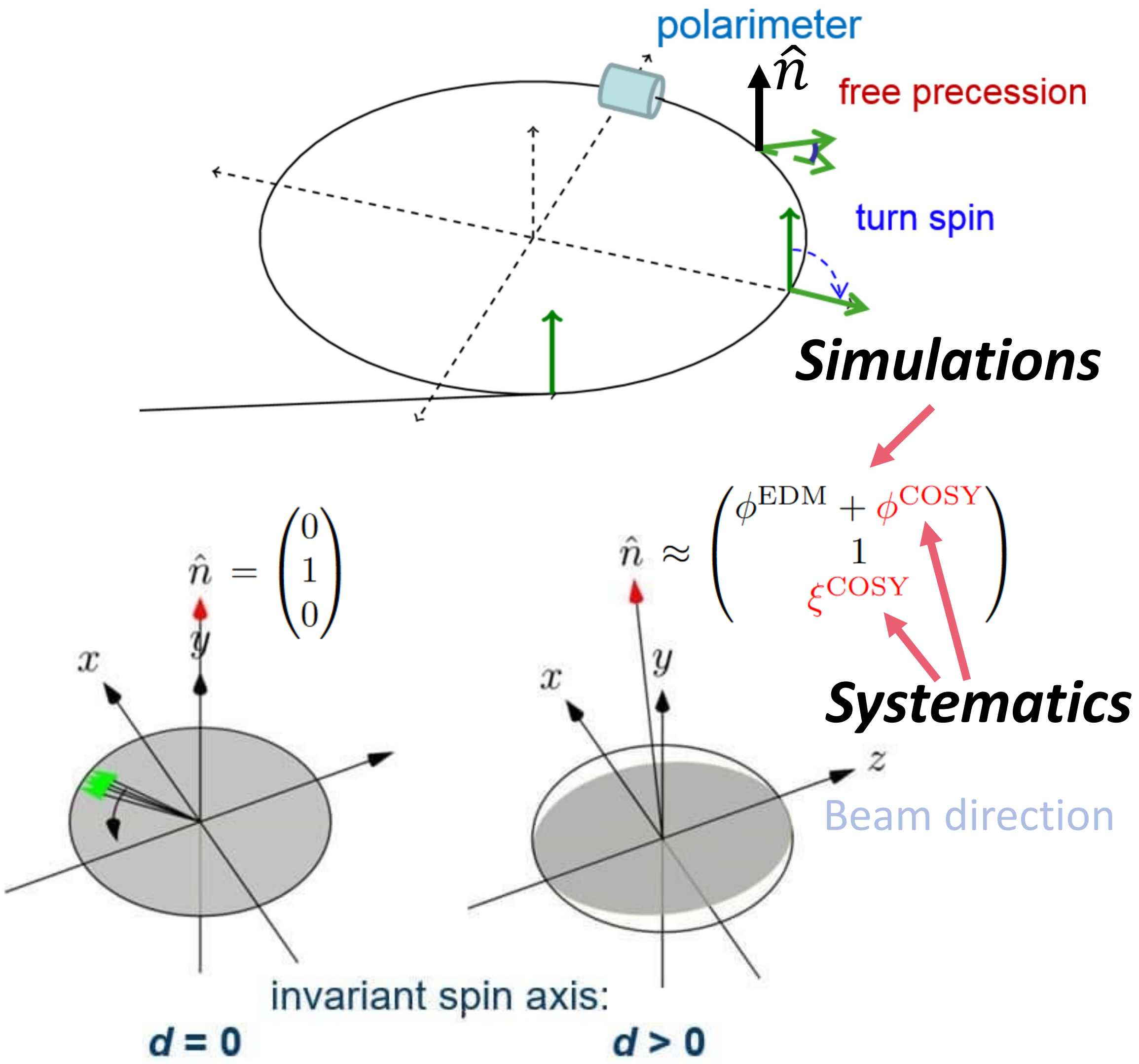
- Non-zero EDM: Tilts $\hat{n}$ in **radial** x direction by ϕ^{EDM} (no longitudinal effect expected)
- **Goal**: Determination of the **orientation** of $\hat{n}$
- **Problem**: Ring **imperfections** (magnet misalignments,..) lead to rotations of $\hat{n}$ in **radial** (x) and **longitudinal** (z) direction



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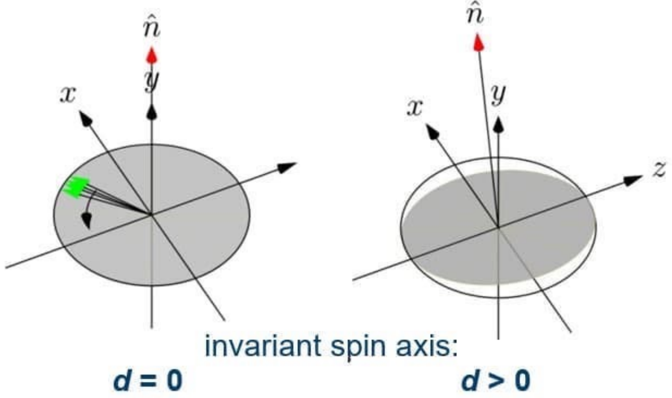
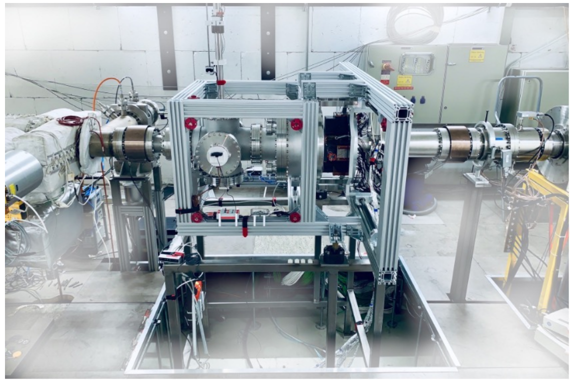
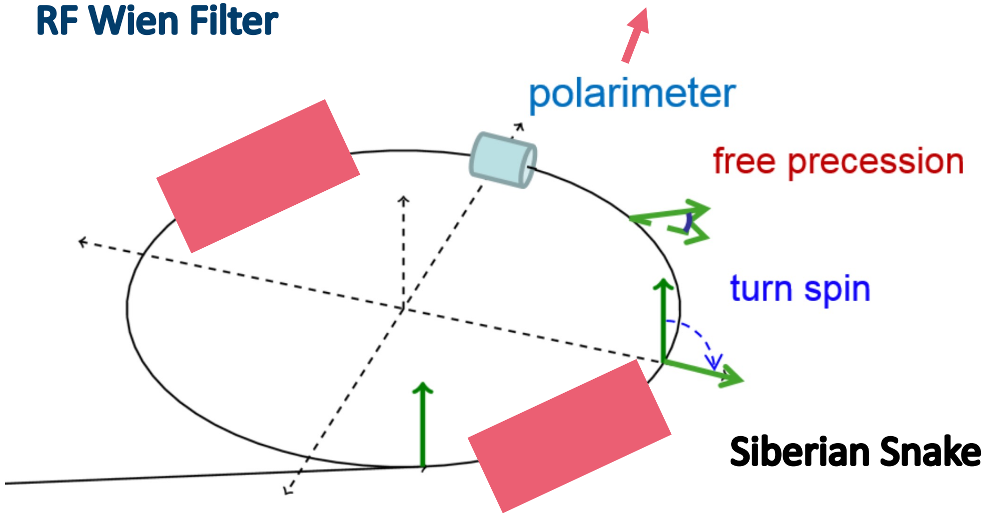
MEASUREMENT PRINCIPLE







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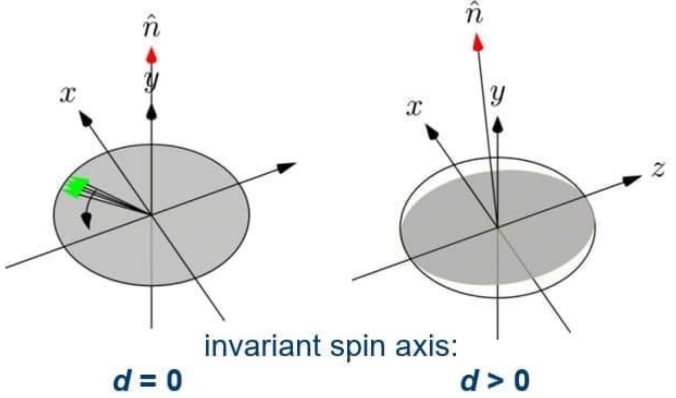

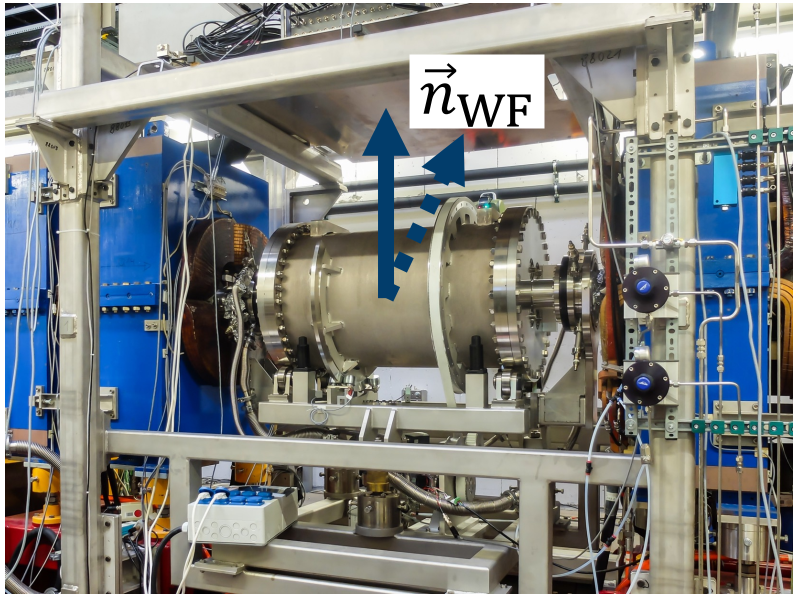

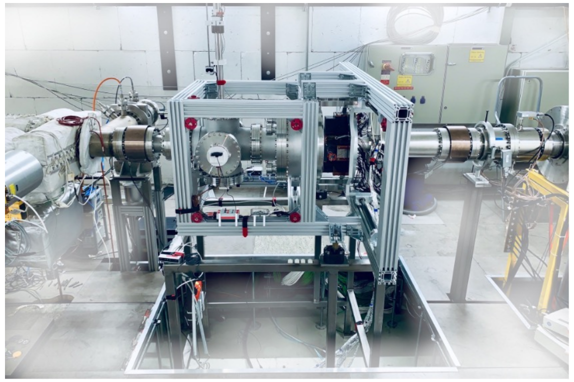

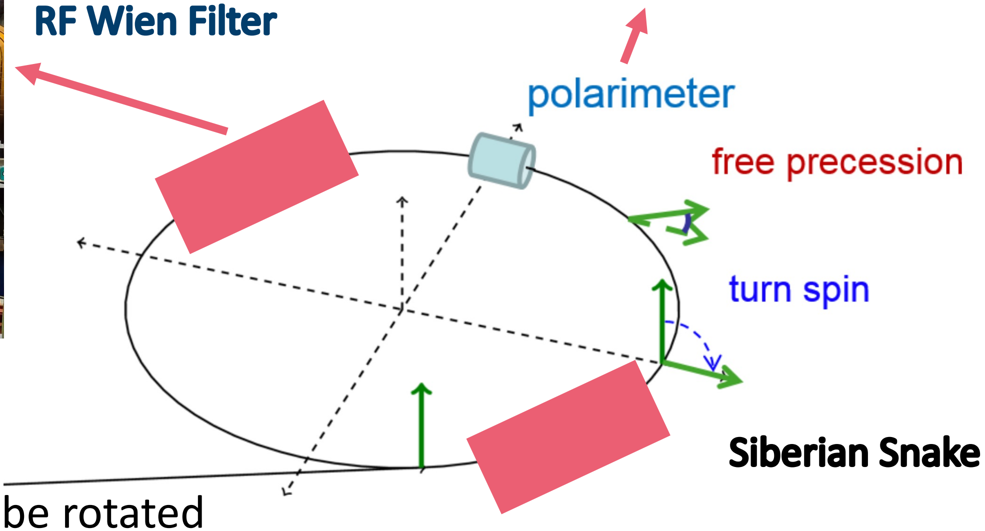

- $\vec{E} \perp \vec{B} \perp$ Beam $\rightarrow \vec{F}_L = 0$
- **Rotational** Device: $\vec{n}_{\mathrm{WF}}$- Field can be rotated around the beam pipe by $\boldsymbol{\phi}^{\mathbf{WF}}$

$$\vec{n}_{\mathrm{WF}} = \begin{pmatrix} \sin\left(\phi^{\mathrm{WF}}\right) \\ \cos\left(\phi^{\mathrm{WF}}\right) \\ 0 \end{pmatrix} \approx \begin{pmatrix} \phi^{\mathrm{WF}} \\ 1 \\ 0 \end{pmatrix}$$

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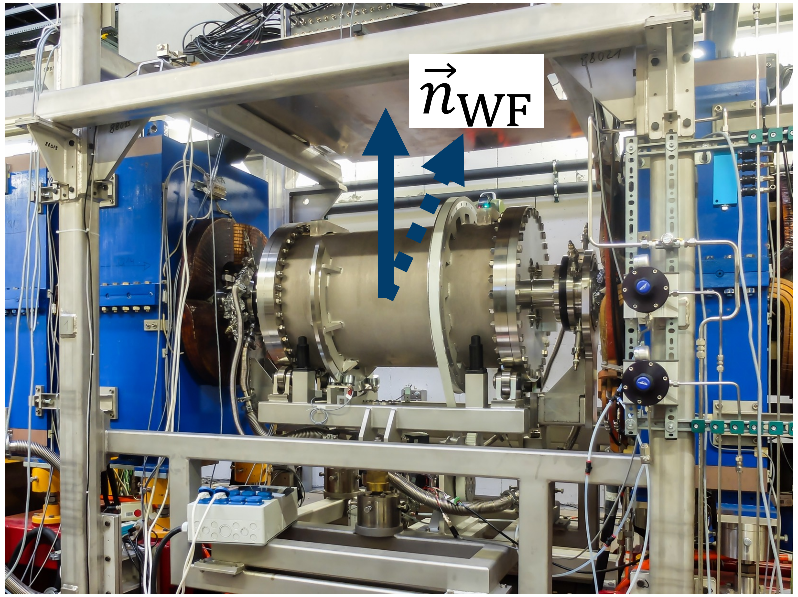
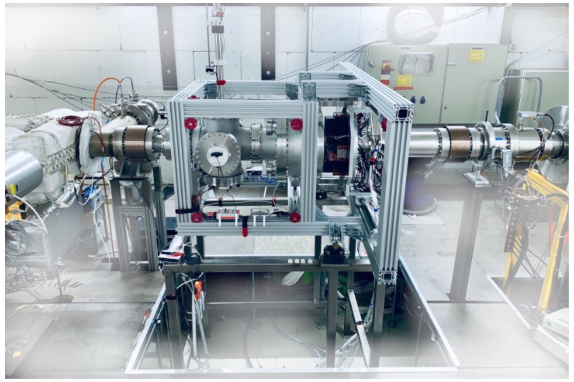
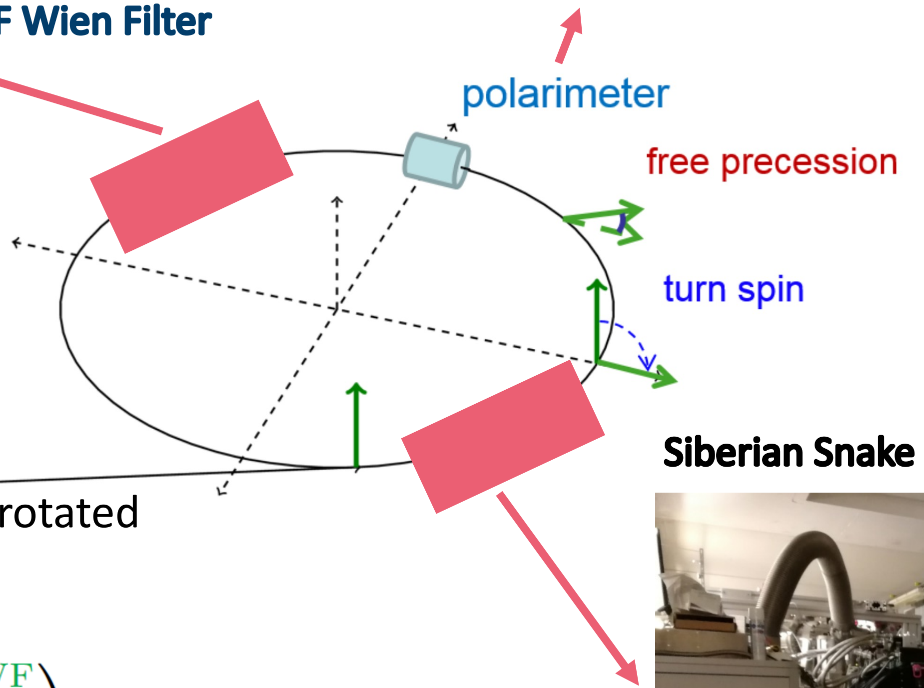
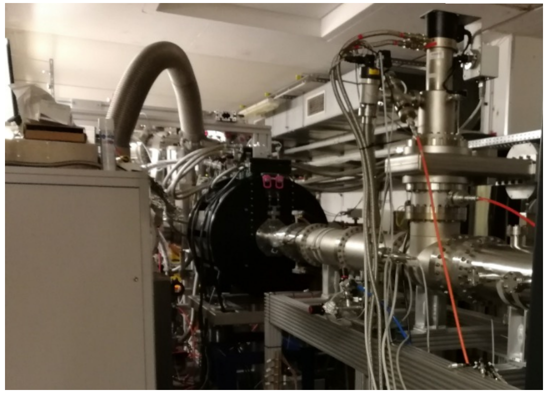
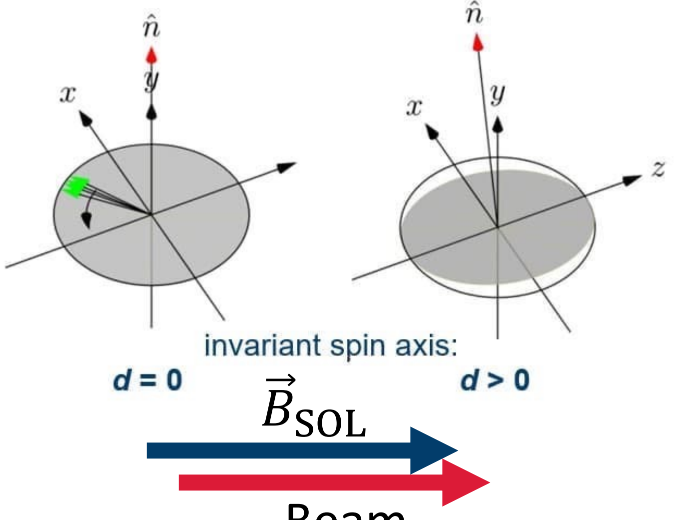
MEASUREMENT PRINCIPLE











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- Longitudinal $\vec{B}$ field $\parallel$ Beam
- $\vec{B}$ - Field kicks $\hat{n}$ in **longitudinal** direction (z) by ξ^{Snake}

$$\vec{n} = \begin{pmatrix} \phi^{\mathrm{EDM}} + \phi^{\mathrm{COSY}} \\ 1 \\ \xi^{\mathrm{Snake}} + \xi^{\mathrm{COSY}} \end{pmatrix}$$

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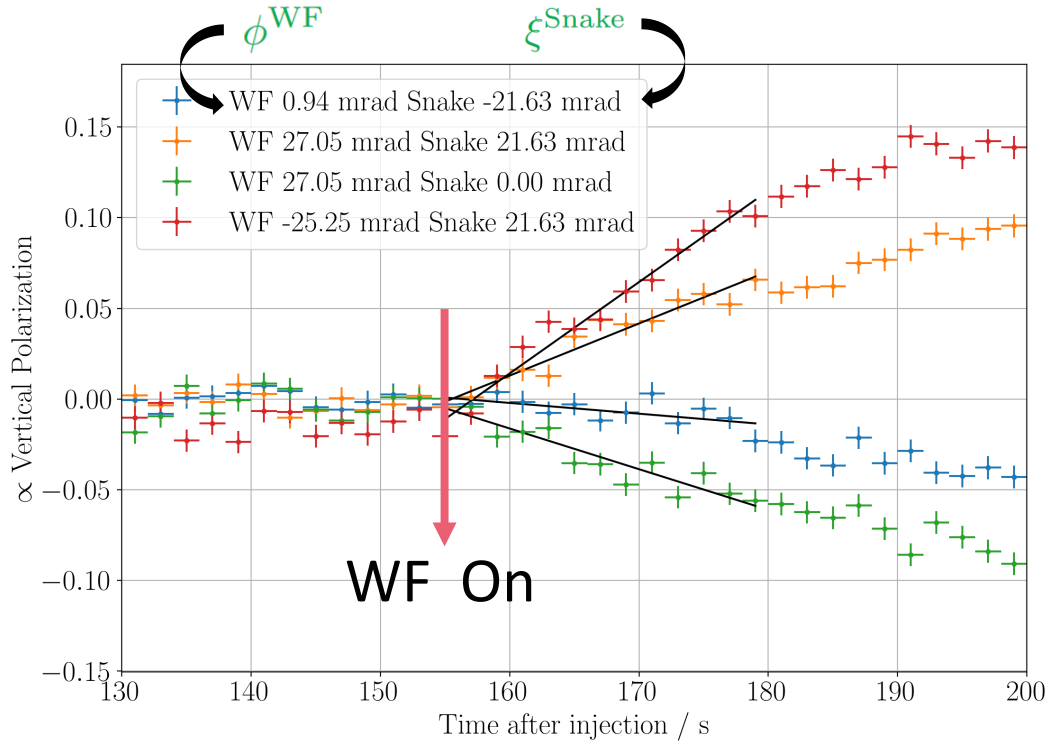
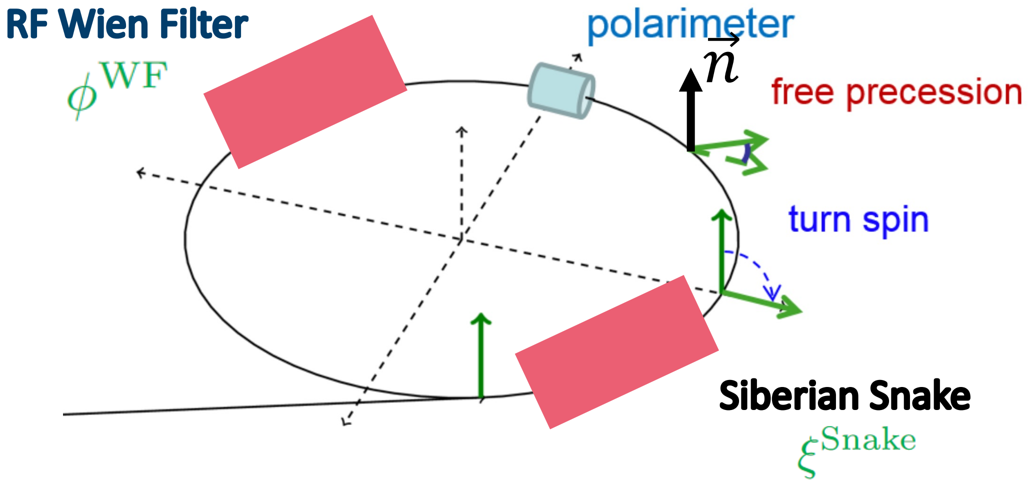
MEASUREMENT PRINCIPLE





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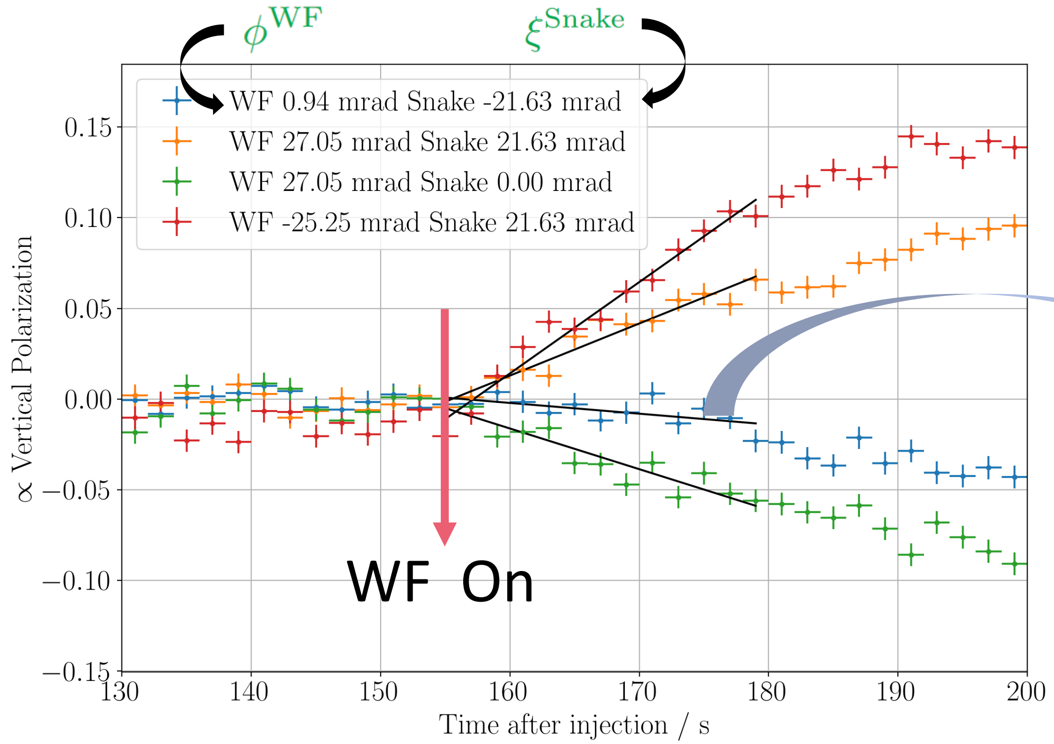


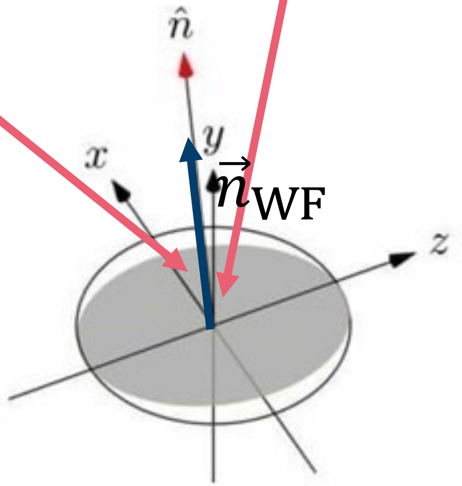
$$\epsilon^2(\phi^{\mathrm{WF}}, \xi^{\mathrm{Snake}}) \propto |\vec{n}_{\mathrm{WF}} \times \vec{n}|^2 \quad \vec{n}_{\mathrm{WF}} : B \text{ field axis of rf Wien filter} \quad \vec{n} : \mathrm{ISA}$$

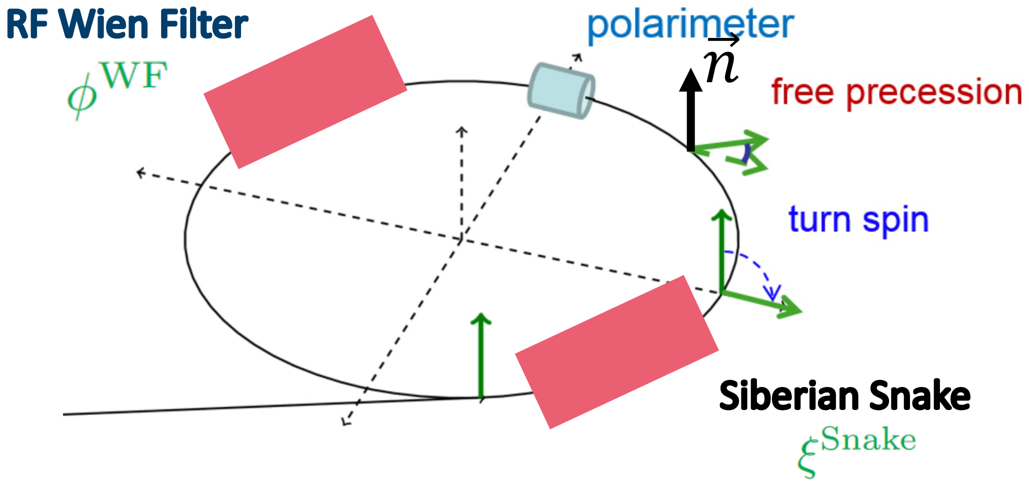
$$\approx \left| \begin{pmatrix} \phi^{\mathrm{WF}} \\ 1 \\ 0 \end{pmatrix} \times \begin{pmatrix} \phi_0^{\mathrm{EDM}} + \phi_0^{\mathrm{COSY}} \\ 1 \\ \xi^{\mathrm{Snake}} + \xi_0^{\mathrm{COSY}} \end{pmatrix} \right|^2$$

$$\approx \left[\left((\phi_0^{\mathrm{EDM}} + \phi_0^{\mathrm{COSY}}) - \phi^{\mathrm{WF}} \right)^2 + \left(\xi^{\mathrm{Snake}} + \xi_0^{\mathrm{COSY}} \right)^2 \right]$$

Build up rate

$$\epsilon \propto \frac{\mathrm{d}}{\mathrm{d}t} p_y(t)$$





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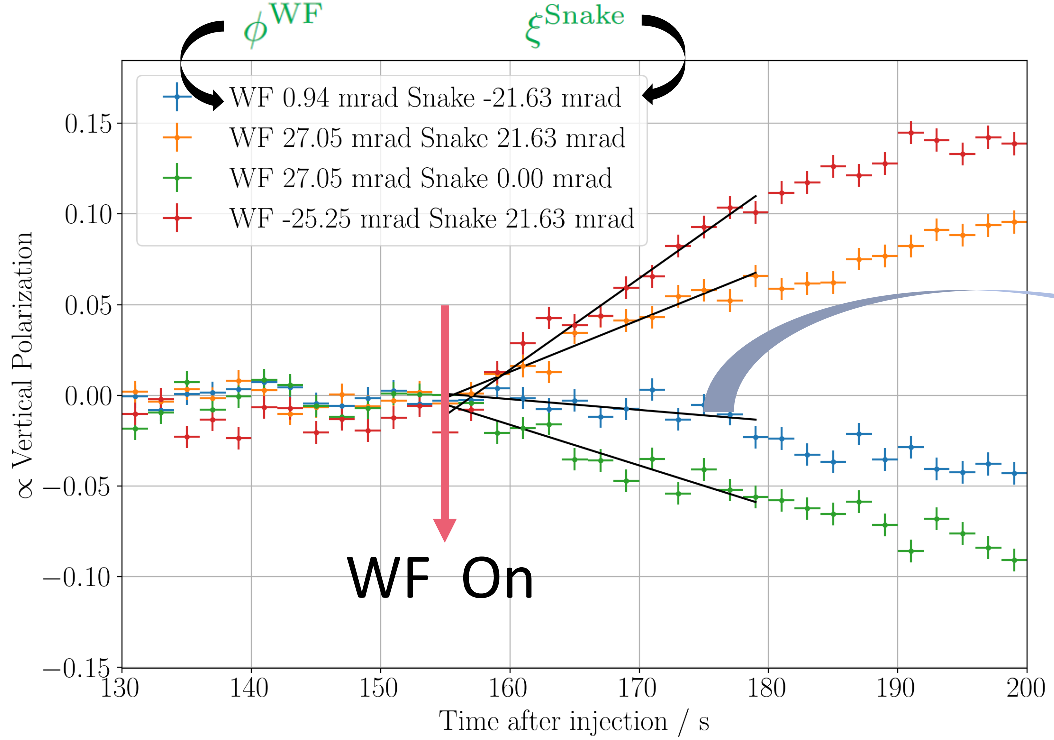
MEASUREMENT PRINCIPLE



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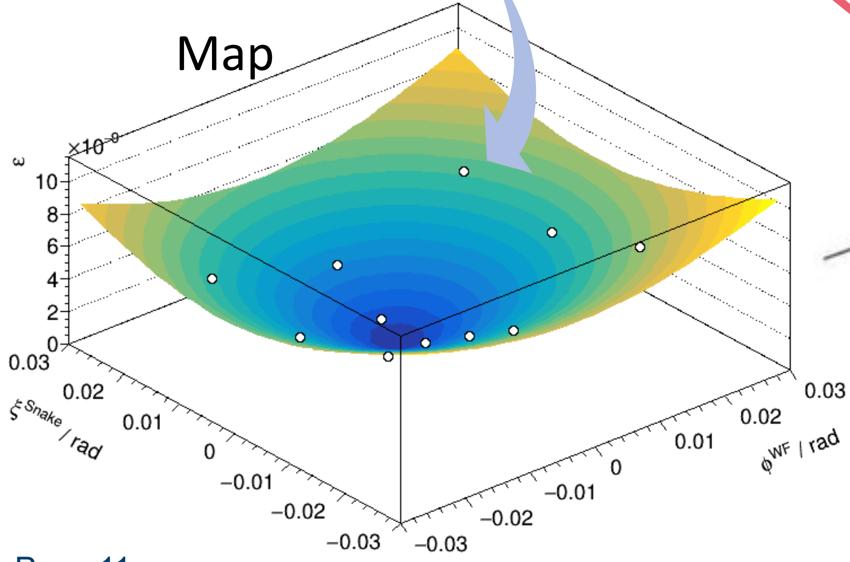
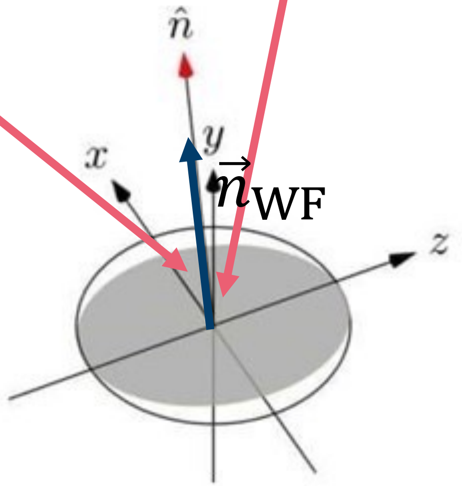
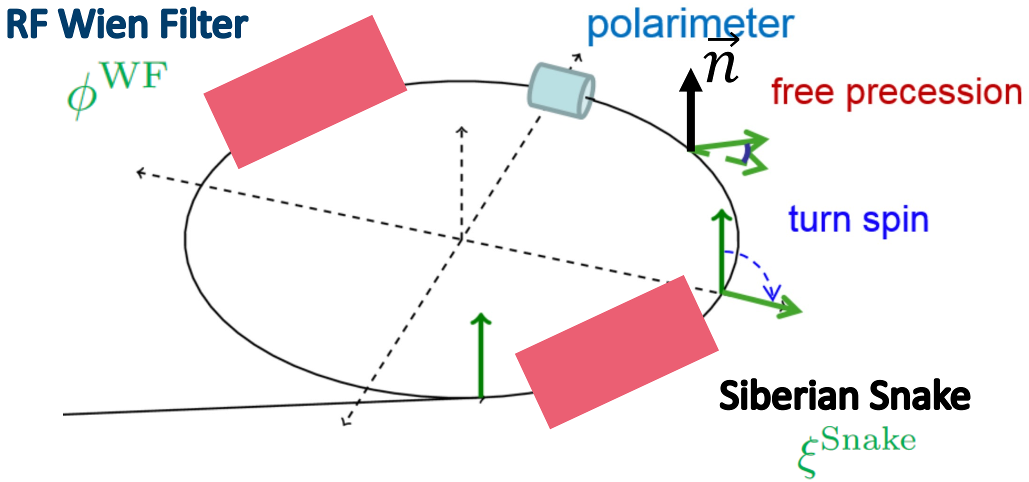
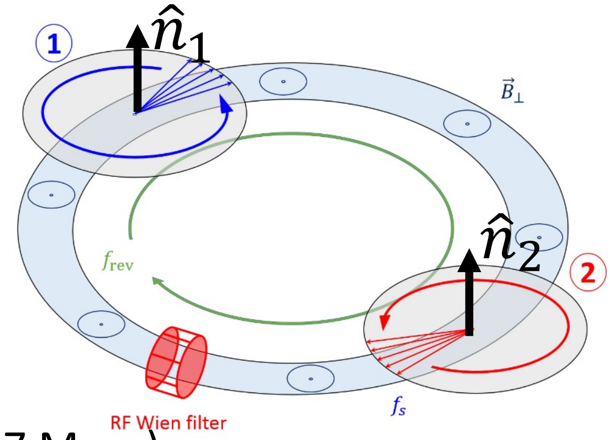
Map







PRELIMINARY RESULTS



$$\epsilon^2(\phi^{\mathrm{WF}}, \xi^{\mathrm{Snake}}) \approx \left[A_1^2 \cdot \left((\phi_0^{\mathrm{EDM}} + \phi_0^{\mathrm{COSY}}) - \phi^{\mathrm{WF}}\right)^2 + A_2^2 \cdot \left(\xi^{\mathrm{Snake}} + \xi_0^{\mathrm{COSY}}\right)^2\right]$$

Precursor 1 (2018)

- 3 weeks of beam time (3 Maps)
- 6 days with **desired** conditions
- Provided **necessary input** for **improvements**

Precursor 1	$\phi_0^{\mathrm{EDM}} + \phi_0^{\mathrm{COSY}}$	ξ_0^{COSY}
Value	$-3.57(5)$ mrad	$-5.55(5)$ mrad

Precursor 2 (2021)

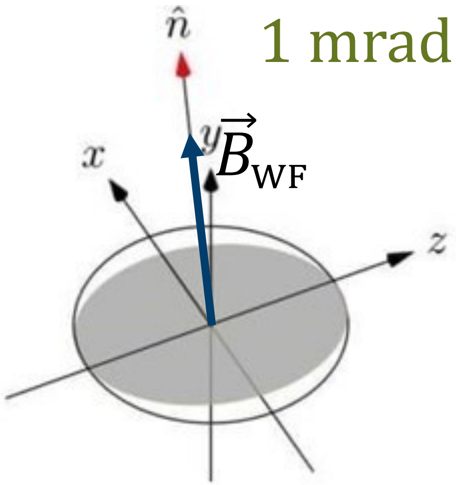
- 5 weeks of beam time (7 Maps)
- Many improvements **compared to 2018**
- New **technique** with two bunches

Precursor 2	$\phi_0^{\mathrm{EDM}} + \phi_0^{\mathrm{COSY}}$	ξ_0^{COSY}
Value	$-1.76(1)$ mrad	$5.53(4)$ mrad

Updates 2018 - 2021

- **Beam Based alignment** of quadrupoles & Siberian Snake
- **Alignment campaigns** of COSY magnet system (Stollenwerk)
- New **Jedi Polarimeter**
- Improved **Matching** ($\vec{F}_L = 0$) of the rf Wien filter

$$1\ \mathrm{mrad} \approx 10^{-17} e \cdot \mathrm{cm}$$



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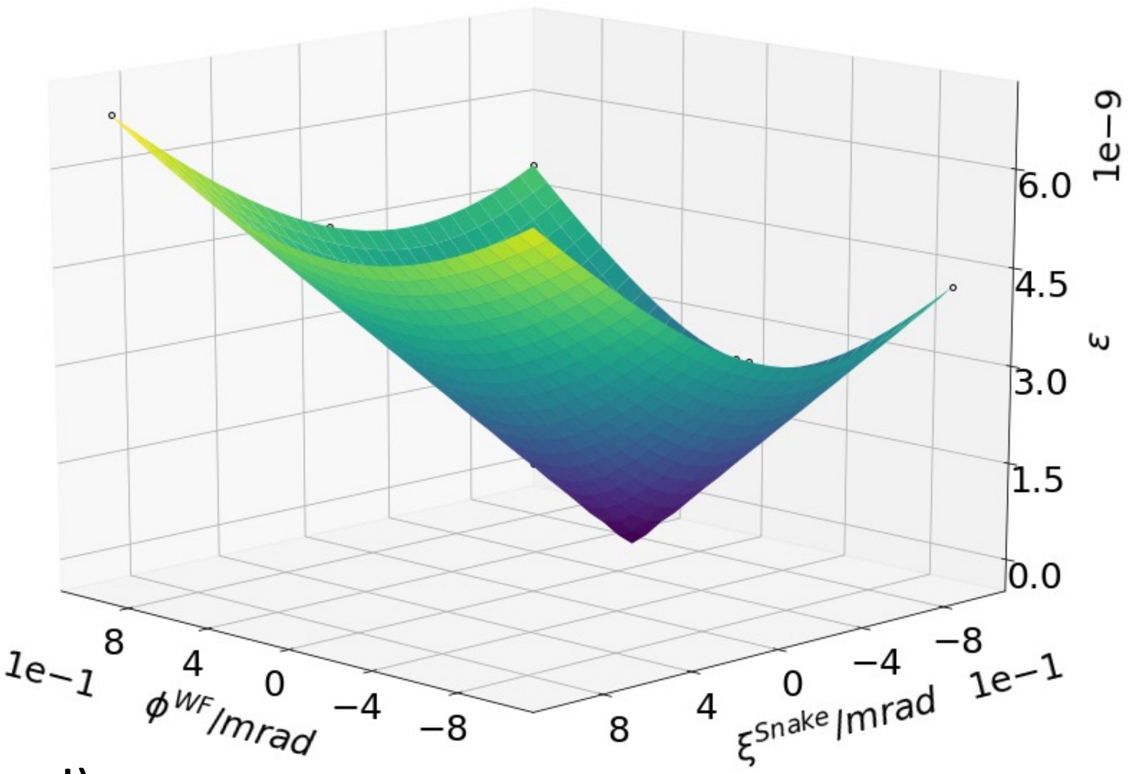
INTERPRETATION

- Bmad **simulation** of the experiment
- Includes **current understanding** of (misaligned) magnets in COSY
- **Simulations predict** tilts of the invariant spin axis not larger than **O(0.1mrad)**
- Measured angles are an **order of magnitude too large**!
- Systematic studies will be used to **understand these angles**
- **Comparison:**

Precursor 2	$\phi_0^{\mathrm{EDM}} + \phi_0^{\mathrm{COSY}}$	ξ_0^{COSY}
Experiment	$-1.76(1)$ mrad	$5.53(4)$ mrad
Simulation	$-0.1119(3)$ mrad	$-0.3697(3)$ mrad

O(1 mrad)

O(0.1 mrad)



Max Vitz (2022)

We are missing something!

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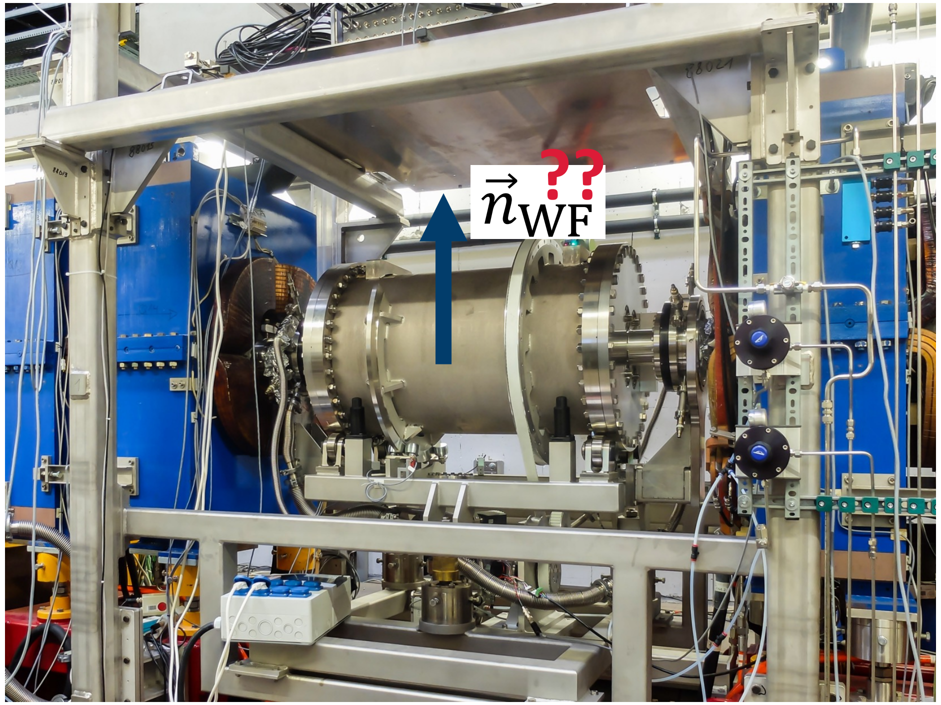
A POSSIBLE SOLUTION



$$\epsilon^2(\phi^{\mathrm{WF}}, \xi^{\mathrm{Snake}}) \propto |\vec{n}_{\mathrm{WF}} \times \vec{n}|^2 \quad \vec{n}_{\mathrm{WF}} : B \text{ field axis of rf Wien filter} \quad \vec{n} : \text{ISA}$$

$$\approx \left| \begin{pmatrix} \phi^{\mathrm{WF}} \\ 1 \\ 0 \end{pmatrix} \times \begin{pmatrix} \phi_0^{\mathrm{EDM}} + \phi_0^{\mathrm{COSY}} \\ 1 \\ \xi^{\mathrm{Snake}} + \xi_0^{\mathrm{COSY}} \end{pmatrix} \right|^2$$

$$\approx \left[\left((\phi_0^{\mathrm{EDM}} + \phi_0^{\mathrm{COSY}}) - \phi^{\mathrm{WF}} \right)^2 + \left(\xi^{\mathrm{Snake}} + \xi_0^{\mathrm{COSY}} \right)^2 \right]$$

- $\vec{B}$- field direction of rf Wien filter is **only known from simulations**
- Depends on **geometrical design -** Predicted Precision O(0.1 mrad)
- We would like to measure the $\vec{B}$- field direction **experimentally**
- **Additional** field components → **change** of the fit formula

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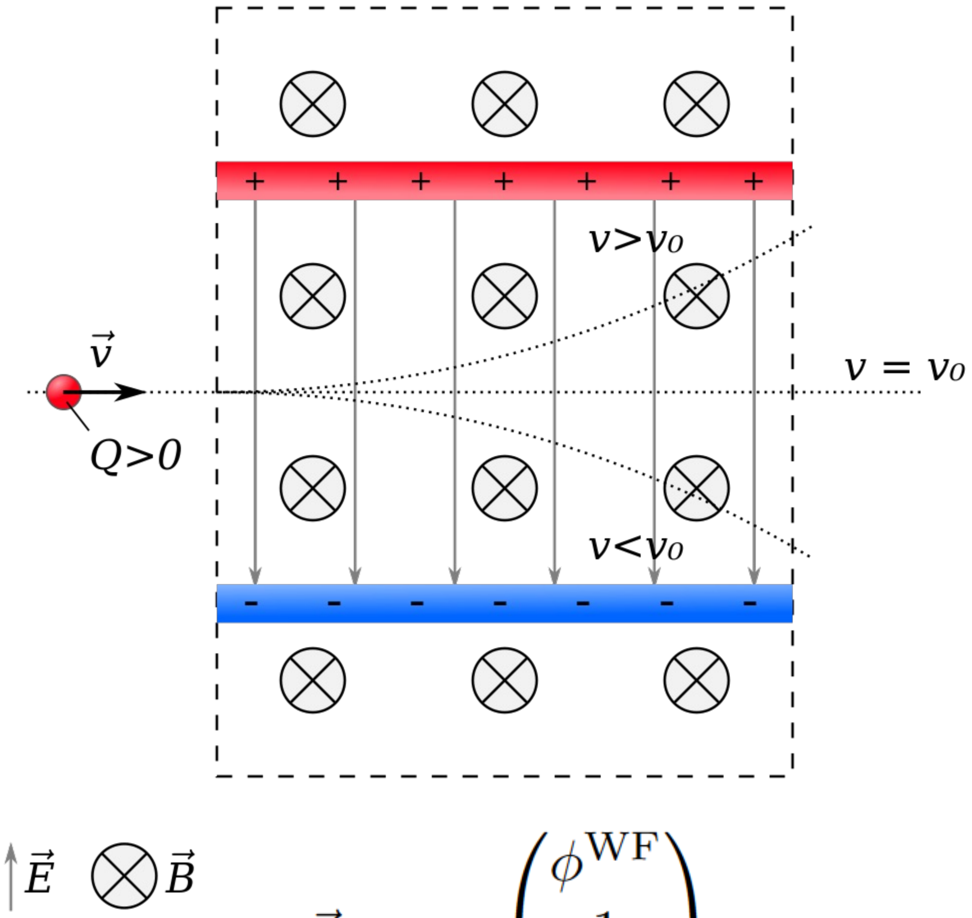
HOW TO MEASURE $\vec{n}_{\mathrm{WF}}$?



$$\vec{n}_{\mathrm{WF}} \approx \begin{pmatrix} \phi^{\mathrm{WF}} \\ 1 \\ 0 \end{pmatrix}$$

- $\vec{E} \perp \vec{B} \perp$ Beam $\rightarrow \vec{F}_L = 0$
- Mismatch the Wien Filter on purpose $\vec{F}_L \neq 0$
- If $\phi_{WF} = 0$ (vertical magnetic field), only **horizontal** beam **displacements** should be observed
- **Unknown** transversal **field** components lead to an orbit **change** in **vertical** direction

- **Problem: Phase Space Coupling** due to longitudinal fields in dipoles, quadrupoles and sextupoles can **mimic** this effect
  - Determined by measuring the **tune shift** for different **quadrupole strengths**

$$\Delta Q = Q_x - Q_y$$

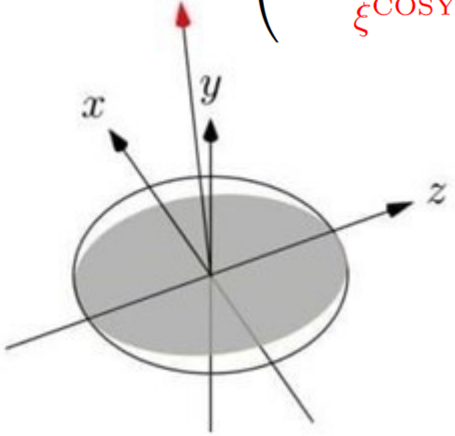
ORBIT MEASUREMENTS

- **Open questions** regarding orbit measurements in COSY
- Not possible to predict the **absolute beam position** with BMAD
- We would like to produce a **systematic** and **consistent** data set of **orbit measurements** to **support** spin tracking simulations

- Starting point is COSY **without correcting steerer magnets**
- See if **measured orbit reacts** the same to **different magnet / steering settings** as in the **simulation**

- If predicted changes in orbit do not coincide with measured orbit changes, the beam might pick up **additional stray fields** not included into our **simulation** which lead to **additional spin rotations**

$$\hat{n} \approx \begin{pmatrix} \phi^{\mathrm{EDM}} + \phi^{\mathrm{COSY}} \\ 1 \\ \xi^{\mathrm{COSY}} \end{pmatrix}$$



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NATURAL CHROMATICITY

- $\xi = \frac{\Delta Q}{Q} / \frac{\Delta p}{p}$ where $\frac{\Delta p}{p} \propto \frac{\Delta f}{f}$ $\longrightarrow$ Cavity RF

  Betatron Tune

  Beam momentum change leads to **orbit change**

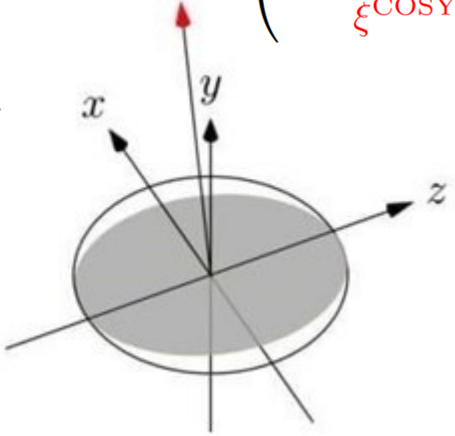
- **Without** sextupole **corrections**

	Horizontal Chromaticity	Vertical Chromaticity
COSY	$\xi_x = -14.91$	$\xi_y = 9.8$
Simulation	$\xi_x = -4.54$	$\xi_y = -3.75$

Total chromaticity

Natural chromaticity

$$\hat{n} \approx \begin{pmatrix} \phi^{\mathrm{EDM}} + \phi^{\mathrm{COSY}} \\ 1 \\ \xi^{\mathrm{COSY}} \end{pmatrix}$$



- **Mismatch** is a hint that nonlinear fields of dipoles and quadrupoles contribute to the measured chromaticity
- **Solution** is to measure the **natural chromaticity**

$$\xi = \frac{\Delta Q}{Q} / \frac{\Delta p}{p} \text{ where } \frac{\Delta p}{p} \propto \frac{\Delta f}{f} \textbf{ and } \frac{\Delta p}{p} = \frac{\Delta B}{B} \longrightarrow \text{No Orbit Change}$$

- Obtain **natural chromaticity** of the linear machine without any correction and effects of **nonlinear fields**
- These effects are **responsible** for the discrepancy between the **measured** chromaticity with sextupoles off and the model

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ALIGNMENT OF THE 2MV SOLENOID

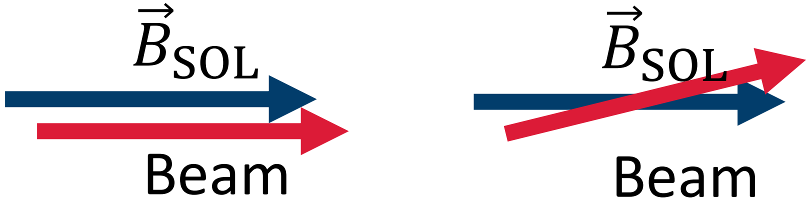
- Map **with two solenoids** in COSY

$$\epsilon^2(\phi^{\mathrm{WF}}, \xi^{\mathrm{Snake}}) \propto |\vec{n}_{\mathrm{WF}} \times \vec{n}|^2 \quad \vec{n}_{\mathrm{WF}} : B \text{ field axis of rf Wien filter} \quad \vec{n} : \text{ISA}$$

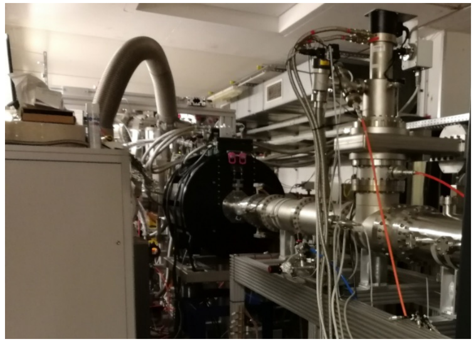
$$\approx \left| \begin{pmatrix} \phi^{\mathrm{WF}} \\ 1 \\ 0 \end{pmatrix} \times \begin{pmatrix} \phi_0^{\mathrm{EDM}} + \phi_0^{\mathrm{COSY}} + \frac{1}{2}\chi^{\mathrm{Sol}} \\ 1 \\ \xi^{\mathrm{Snake}} + \xi_0^{\mathrm{COSY}} + \chi^{\mathrm{Sol}} \end{pmatrix} \right|^2$$

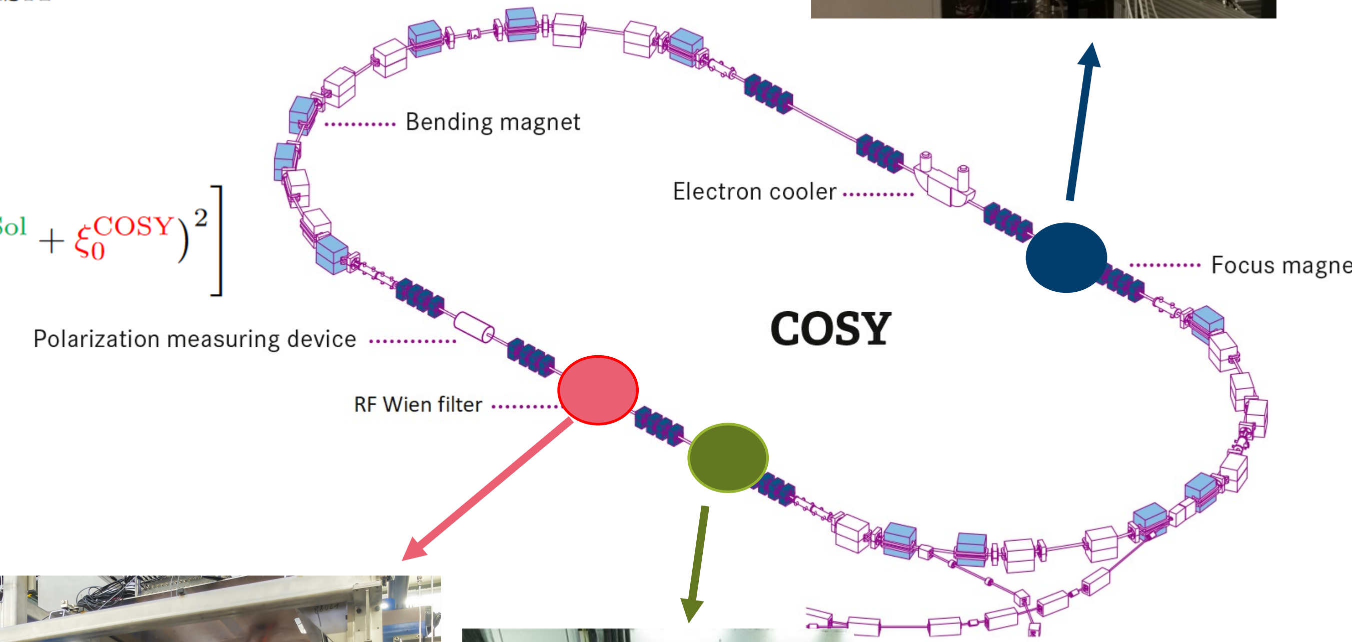
$$\approx \left[\left((\phi_0^{\mathrm{EDM}} + \phi_0^{\mathrm{COSY}}) - \phi^{\mathrm{WF}} + \frac{1}{2}\chi^{\mathrm{Sol}} \right)^2 + (\xi^{\mathrm{Snake}} + \chi^{\mathrm{Sol}} + \xi_0^{\mathrm{COSY}})^2 \right]$$

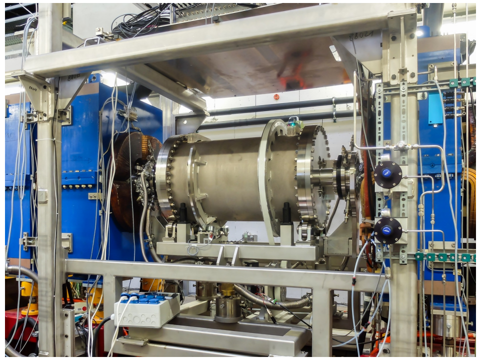
- **Problem**: Formula only valid if **Beam** ∥ $\vec{B}$ **field** axis in solenoid



- Need to correct fit formula if **Beam** ∦ $\vec{B}_{\mathrm{SOL}}$







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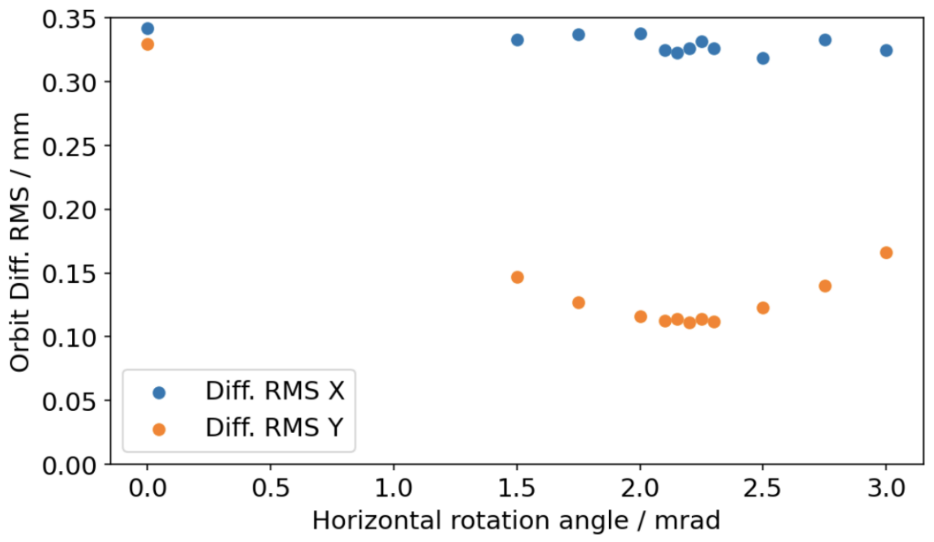
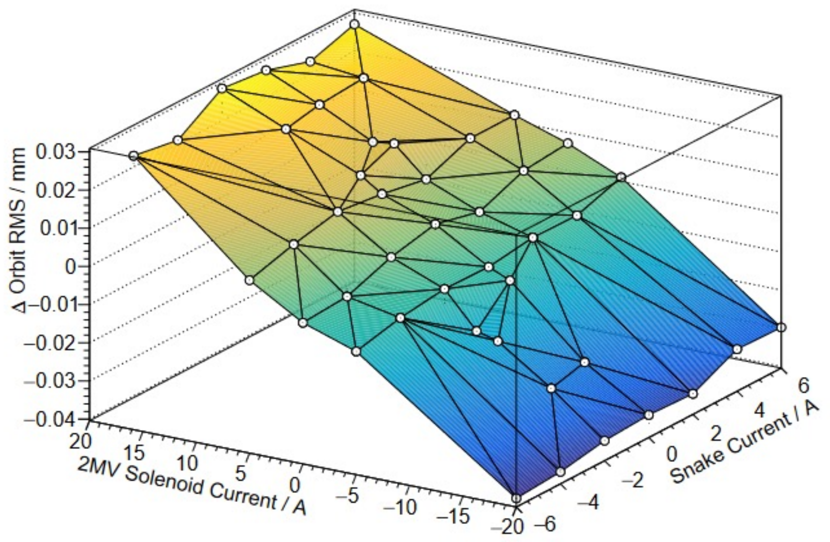
ALIGNMENT OF THE 2MV SOLENOID

- Alignment campaign of the Siberian Snake in 2020
- If **Beam**$\nparallel \vec{B}_{SOL}$ beam gets steered
- By changing the beam path through the solenoid, the Orbit RMS change needs to be minimized

- Alignment of the Siberian Snake



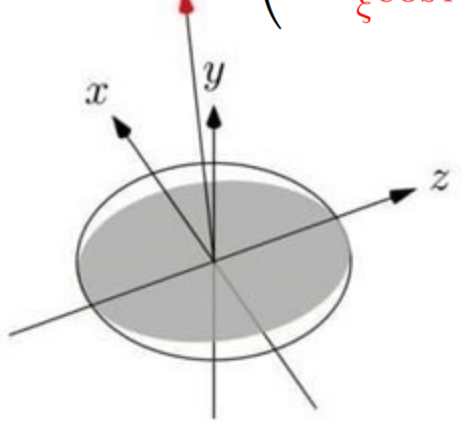
- Horizontal Orbit RMS change



SUMMARY

Precursor 2	$\phi_0^{\mathrm{EDM}} + \phi_0^{\mathrm{COSY}}$	ξ_0^{COSY}
Experiment	$-1.76(1)\,\mathrm{mrad}$	$5.53(4)\,\mathrm{mrad}$
Simulation	$-0.1119(3)\,\mathrm{mrad}$	$-0.3697(3)\,\mathrm{mrad}$

$$\hat{n} \approx \begin{pmatrix} \phi^{\mathrm{EDM}} + \phi^{\mathrm{COSY}} \\ 1 \\ \xi^{\mathrm{COSY}} \end{pmatrix}$$



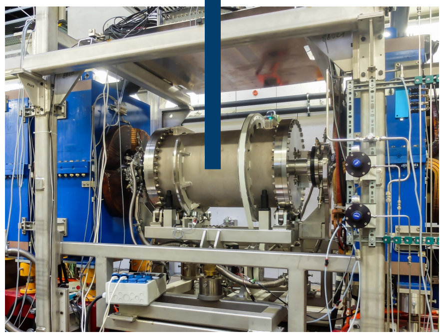
- Apply for **two weeks of beam time**
- Measured orientation of $\vec{n}$ **can not be explained by simulations**
- Measure the **orientation of $\vec{n}_{WF}$**

$$\epsilon^2(\phi^{\mathrm{WF}}, \xi^{\mathrm{Snake}}) \propto |\vec{n}_{\mathrm{WF}} \times \vec{n}|^2 \quad \vec{n}_{\mathrm{WF}} : B \text{ field axis of rf Wien filter} \quad \vec{n} : \mathrm{ISA}$$

$$\approx \left| \begin{pmatrix} \phi^{\mathrm{WF}} \\ 1 \\ 0 \end{pmatrix} \times \begin{pmatrix} \phi_0^{\mathrm{EDM}} + \phi_0^{\mathrm{COSY}} \\ 1 \\ \xi^{\mathrm{Snake}} + \xi_0^{\mathrm{COSY}} \end{pmatrix} \right|^2$$

$$\approx \left[\left((\phi_0^{\mathrm{EDM}} + \phi_0^{\mathrm{COSY}}) - \phi^{\mathrm{WF}} \right)^2 + \left(\xi^{\mathrm{Snake}} + \xi_0^{\mathrm{COSY}} \right)^2 \right]$$

$\vec{n}_{WF}$??



- Measurements to **improve** our **models** of COSY
  - Systematic **Orbit measurements** to find field imperfections
  - Measurement of **natural chromaticity**
  - Measure **Alignment** of the **2 MV Solenoid**
- These measurements can <u>only be done in COSY</u> are needed to <u>finalize the EDM experiment and fulfill the milestone in the current POF period</u>

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BACK UP

BEAM REQUEST

Topic	**Tasks**	**Estimated Beam Time**
Orbit studies	Setup and preparation of tools	2 days
	Measurements at injection energy	1 day
	Measurements at 970 MeV/c	1 day
Wien filter studies	Final setup of Wien filter with beam	
	Preparation of measurement tools	
	Preparation of solenoid	
	in total (partially in parallel)	3 day
	Measurements at 0°	2 days
	Measurements at 90°	2 days
	Orbit studies	1 day
2 MV solenoid	Beam based alignment	1 day
Chromaticity		1 day
	Total	**14 days**

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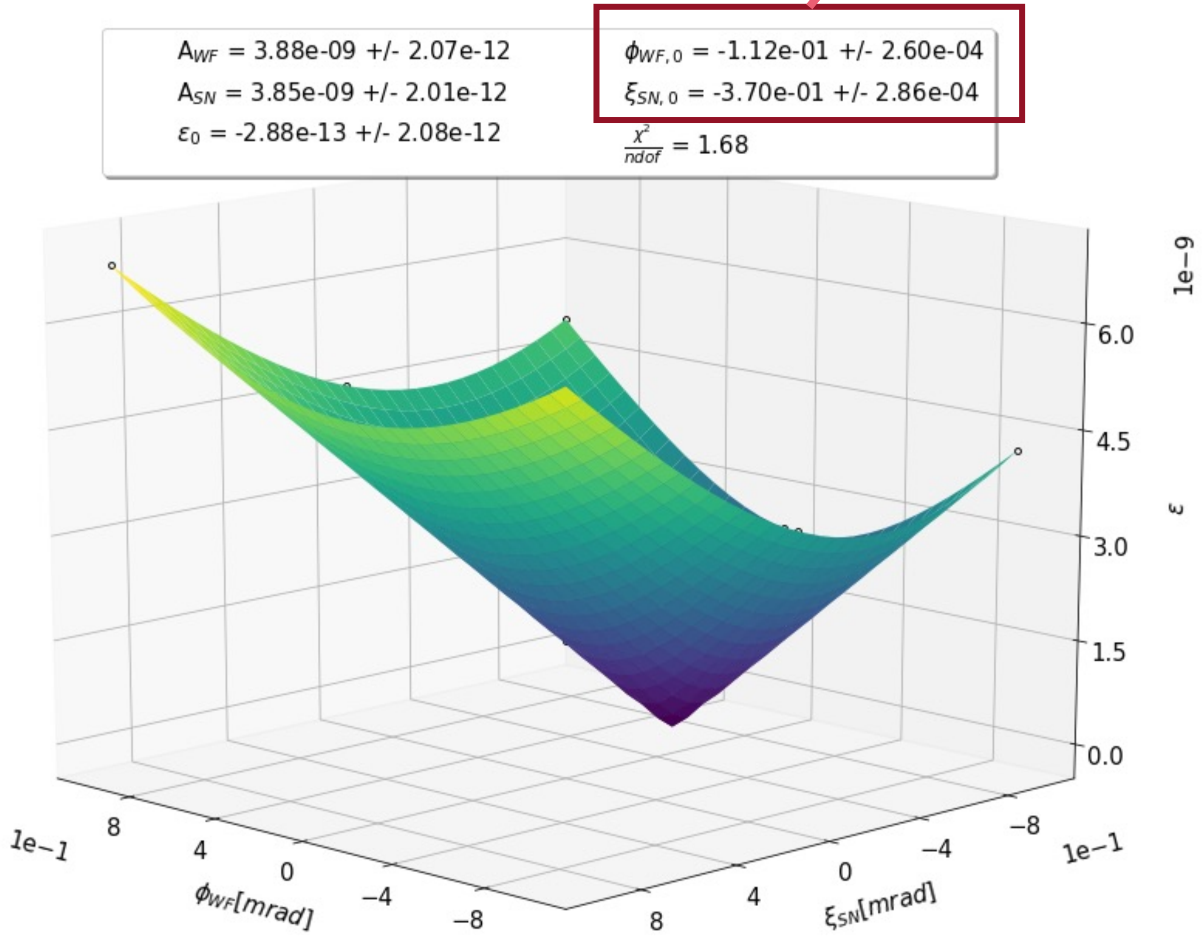
SIMULATION REVISITED

O(0.1 mrad) ??

- Many **open questions** still need to be adressed regarding beam & spin tracking **simulations**

- **Mapping Field Imperfections** using Orbit Measurements
- **Natural Chromaticity** Measurements
- **Measurements at COSY** support our current understanding of **simulations**
- Problems with **absolute values**



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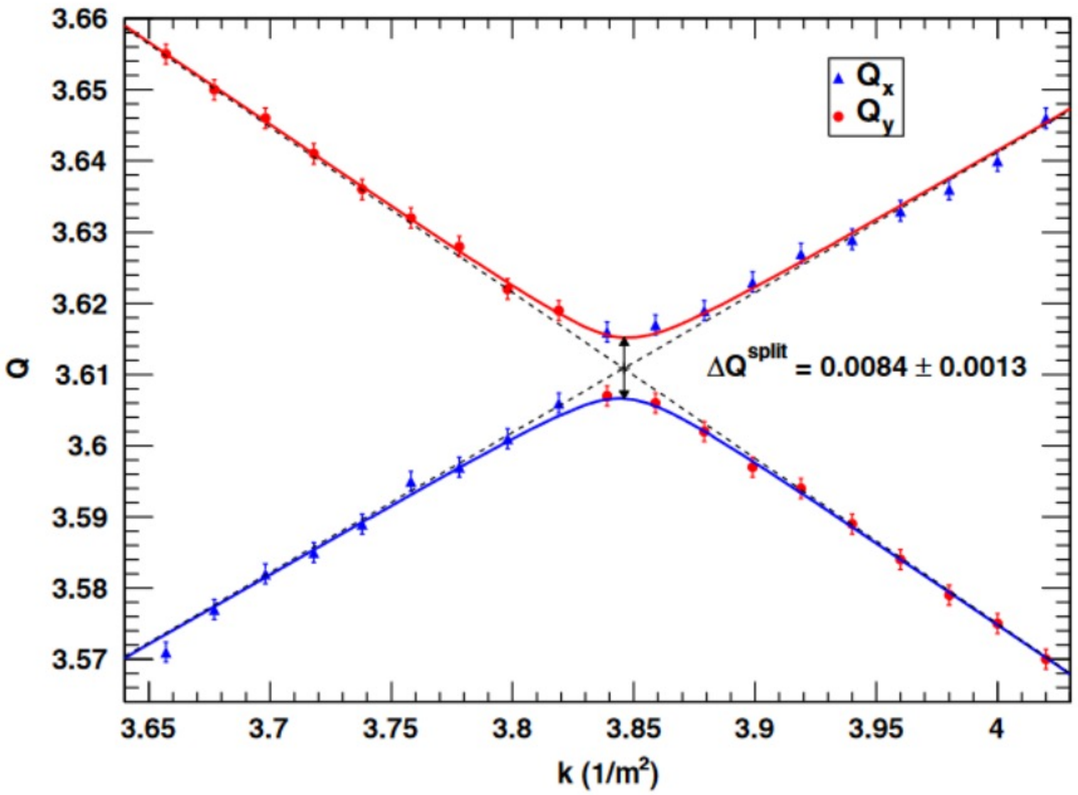
PHASE SPACE COUPLING



- **Problem:** Phase Space Coupling due to multipoles in dipoles, quadrupoles and sextupol can **mimic** this effect
- Coupling can be measured with the **tune split**

$$\Delta Q = Q_x - Q_y$$

- Measure horizontal and vertical **betatron tune** as function of **quadrupole strength** k
- To **correlate** the **measured momentum kick** with the phase-space coupling and the **observed tune split** one can use the existing solenoids (snake, 2 MV cooler) for **calibration**