First electric dipole moment measurement of the deuteron with the waveguide RF Wien Filter

Investigation of Systematic Effects

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Spokespersons for beam time:

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Is support* from the LSF program of the EU requested?

Yes ~~No~~

Total number of particles and type of beam (p,d,polarization)	Momentum range (MeV/c)	Intensity or internal reaction rate (particles per second) minimum needed	Intensity or internal reaction rate (particles per second) maximum useful
unpolarized deuterons	p = 970 MeV/c	10^9	10^{10}
Experimental area	**Safety aspects (if any)**	**Earliest date of Installation**	**Total beam time (No.of shifts)**
COSY ring, incl. electron cooler, snake, 2 MV solenoid, Wien filter		next scheduling period	2 weeks

What equipment, floor space etc. is expected from Forschungszentrum Jülich/IKP?

***EU-Support:**
The European Commission supports access to COSY for users outside Germany from European and associated states within the STRONG-2020 integrating activity.
For details see http://www.ikp.fz-juelich.de/strong2020.

Description of request (motivation, milestone(s), goals; maximum 5 pages)

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The JEDI collaboration performed two beam times in December 2018 and February 2021 to measure the electric dipole moment of the deuteron. The analysis is quite advanced and revealed several open questions in the interpretation of the results with respect to a value/limit for the electric dipole moment of the deuteron. This is due to systematic effects in the COSY ring that are not well understood. Therefore, further studies are essential for a successful conclusion of the precursor experiment at COSY and the corresponding milestone in the POF topic Cosmic Matter in the laboratory.

In this proposal, we outline several studies that address these systematic effects. They all require only an unpolarized deuteron beam.

1 Introduction

Electric Dipole Moments (EDM) of elementary particles are one of the most sensitive tools for the study of physics beyond the Standard Model (BSM), since they break both parity (P) and time-reversal invariance (T) — and, assuming that the CPT theorem holds, also charge parity (CP). The latter is one of the key prerequisites for understanding the apparent asymmetry between matter and antimatter in the universe. Non-zero EDMs exist within the Standard Model, however, these are too small to explain the observed dominance. Therefore, a measurement of EDMs larger than the predictions from the Standard Model would hint towards physics behind the SM and contribute to our understanding of our universe.

The goal of the JEDI collaboration with the precursor experiment is a first direct measurement of the deuteron EDM. It is part of a staged approach towards a dedicated high precision, all-electric storage ring for protons (see [1]) and one of the main objectives of an Advanced Grant of the European Research Council [2], awarded in 2015. It is also defined as milestone CML-2 in the current POF topic *Cosmic Matter in the Laboratory* within the research field *Matter*.

1.1 Measurement principle

The EDM of an fundamental particle is aligned with its spin direction. The spin motion in magnetic and electric fields is described by the generalized Thomas-BMT equation [3]:

$$
\begin{aligned}
\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} &= \left(\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}}\right) \times \vec{S}\,, \\
\vec{\Omega}_{\mathrm{MDM}} &= -\frac{q}{m}\left[\left(G + \frac{1}{\gamma}\right)\vec{B} - \frac{\gamma G}{\gamma+1}\vec{\beta}\left(\vec{\beta}\cdot\vec{B}\right) - \left(G + \frac{1}{\gamma+1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right], \\
\vec{\Omega}_{\mathrm{EDM}} &= -\frac{q}{m}\frac{\eta_{\mathrm{EDM}}}{2c}\left[\vec{E} - \frac{\gamma}{\gamma+1}\vec{\beta}\left(\vec{\beta}\cdot\vec{E}\right) + c\,\vec{\beta}\times\vec{B}\right].
\end{aligned}
$$

Based on these equations, the spin motion in a storage ring can be characterized by the so-called invariant spin axis $\vec{n}$ (or stable spin axis, *i.e.* the spin direction of a particle that remains the same after one full turn) and the spin tune ν_s (the number of spin revolutions about the invariant spin axis per turn). In an ideal storage ring and in absence of an EDM, the invariant spin axis is vertical. In this case, if one starts with a spin direction within the ring plane, the spin starts precessing about the invariant spin axis and stays in the plane. A non-zero EDM would result in a radial tilt of the invariant spin axis. For particles like protons with a gyroscopic anomaly $G > 0$ in an all-electric ring one can choose the momentum such, that $\vec{\Omega}_{\mathrm{MDM}}$ vanishes (frozen spin) and $\vec{\Omega}_{\mathrm{EDM}}$ causes an out-of-plane spin rotation (see [1]).

In a magnetic ring like COSY the situation is different. Here the spin precession cannot be canceled and the spin tune is given by $\nu_s = \gamma G$. The tilt of the invariant spin axis caused by an EDM is $\xi = \frac{\eta_{\mathrm{EDM}}\beta}{2G}$ in radial direction producing a (small) oscillation of the vertical spin component when starting in ring plane. In order to generate a net result, additional tools are needed: it has been shown that using an RF Wien filter with the magnetic field axis $\vec{n}_{\mathrm{WF}}$ aligned to the invariant spin axis without EDM (*i.e.* vertical for an ideal ring), the EDM-induced spin rotations can be accumulated when the Wien filter is operated in phase with the spin precession of the stored particles (see Refs. [4–6]). The rf Wien filter then acts as a spin rotator with the resonance strength

$$\varepsilon = \frac{1}{4\pi}|\vec{n} \times \vec{n}_{\mathrm{WF}}|\psi_{\mathrm{WF}}, \tag{1}$$

where ψ_{WF} is the spin rotation angle per single pass.

This concept has been implemented in two experimental runs at COSY, one in December 2018 and one in February 2021 [7, 8]. In order to maintain the resonance condition of the rf Wien filter a phase-lock feedback had been implemented keeping the relative phase between the Wien filter frequency and the spin precession constant [9]. In addition, the experimental setup allowed intentional variations of $\vec{n}$ and $\vec{n}_{\mathrm{WF}}$ for systematic investigations:

(i) A spin rotation of ξ^{Sol} around the longitudinal axis by a Siberian snake in the opposite straight of COSY produces an additional longitudinal tilt of $\vec{n}$ by $\frac{\xi^{\mathrm{Sol}}}{2\sin(\pi\nu_s)}$ at the position of the RF Wien filter.

(ii) The RF Wien filter can be rotated by an angle ϕ^{WF} about its longitudinal axes changing $\vec{n}_{\mathrm{WF}}$.

If one rewrites $\vec{n} \times \vec{n}_{\mathrm{WF}}$ in Eq. (1) using these additional rotations and considers the tilt angles small, one gets

$$\varepsilon^2 = \frac{\psi_0^2}{16\pi^2}\left[\left(\phi^{\mathrm{WF}} - \phi_0^{\mathrm{WF}}\right)^2 + \left(\frac{\xi^{\mathrm{Sol}}}{2\sin(\pi\nu_s)} + \xi_0^{\mathrm{Sol}}\right)^2\right], \tag{2}$$

where ξ_0^{Sol} and ϕ_0^{WF} describe the direction of invariant spin axis $\vec{n}$ at the position of Wien filter (the resonance strength vanishes when $\vec{n} \parallel \vec{n}_{\mathrm{WF}}$). Thus, by measuring a map $\varepsilon = f(\xi^{\mathrm{Sol}}, \phi^{\mathrm{WF}})$ and fitting Eq. (2) one can determine the direction of $\vec{n}$. An upper limit of the deuteron EDM can then be extract by a comparison with simulations assuming $\eta_{\mathrm{EDM}} = 0$.

For the determination of ε for each setting we used two different methods:

(i) In Precursor run I we used a single bunch, and the phase-lock feedback as well as the rf Wien filter were acting on the same particles. As the feedback system requires a minimum degree of in-plane polarization to work, the measurement stopped as soon as the out-of-plane spin rotation into the vertical direction was complete. In this setup the slope of the out-of-plane angle $\alpha(n)$ as a function of the turn number n in COSY depends on the relative phase ϕ_{rel} between the Wien filter frequency and the spin precession:

$$\frac{1}{2\pi}\frac{\mathrm{d}\alpha}{\mathrm{d}n} = \varepsilon \sin(\phi_{\mathrm{rel}} + \Delta\phi) \tag{3}$$

In order to determine ε we typically measured 9 relative phases per setting.

(ii) For Precursor run II we implemented a system of fast switches at the Wien filter that allowed us to perform bunch-selective spin manipulations. Thus, we used two bunches in the machine, one for the phase-lock feedback ("pilot bunch") and one for spin rotations by the RF Wien filter. Here we measured the (phase independent) vertical oscillation frequencies $f_y = \varepsilon \cdot f_{\mathrm{rev}}$ to extract ε.

1.2 Status

An more detailed overview on the current preliminary results from the two precursors runs are given in Sec. 2. Here is a short summary together with some open question we'd like to address with this proposal:

- The radial and longitudinal orientation of the invariant spin axis measured with the Wien filter scans is about $3\,\mathrm{mrad}$ and $\pm 5\,\mathrm{mrad}$, respectively. While we had several campaigns to mechanically align the COSY components between the two runs and also calibrated the beam position monitors using beam based alignment, the magnitude of both values changed only slightly. It lead, however, to significant improvements at other places, like the reduced steerer corrections necessary for an optimal orbit. With the current knowledge on COSY and the Wien filter, simulations can hardly reproduce tilts larger than $1\,\mathrm{mrad}$. Therefore, we propose the following systematic studies:

  (i) The large tilts might be connected to stray fields and other field imperfections which we plan to map using extensive orbit studies with varying field strength. This might also be the reason for the sign change in the longitudinal tilt between both experiments as we were running on different orbits. (Section 3) Another way to check the influence of nonlinear fields is the comparison of the total versus the natural chromaticity. We address this in Sect. 6.

  (ii) From design constraints and dedicated simulations of the device and the resonant circuit the electric and magnetic field axes in the Wien filter should be vertically and horizontally aligned better than $0.1\,\mathrm{mrad}$. We want to verify this by running the Wien filter in quasi-static mode studying the impact on the orbit. (Section 4)

- The longitudinal tilt of the invariant spin axis can - in principle - also be extracted by means of the solenoids measuring the spin tune change as function of the solenoid strength. Here we got values that are nearly 2 orders of magnitude smaller than the ones measured with the Wien filter. However, one has to note that

  (i) this probes the invariant spin axis at the position of the solenoid, not at the Wien filter and,

  (ii) this is only valid for an ideal ring and misalignments of beam and solenoid will have an impact on the result.

  While the Siberian snake had been aligned before Precursor run II, the alignment of the 2MV Cooler solenoid is not known as precise. Therefore, we would like to perform a measurement using beam based alignment (as it was done for the snake). (Section 5)

- In precursor run II we repeated the measurements from precursor run I in order to compare the slope measurements with the pilot-bunch measurements. The results were fully consistent.

To summarize, with this proposal we aim at a consistent understanding of these results for both runs experimentally as well as from beam and spin tracking simulations. This is a crucial step for finalizing our precursor studies at COSY.

2 Preliminary Results from the Precursor Runs

In the following the current status for (i) the determination of the invariant spin axis using the rf Wien filter and (ii) the measurements with the siberian snake and the 2 MV electron cooler are discussed. Table 1 shows the typical beam parameters.

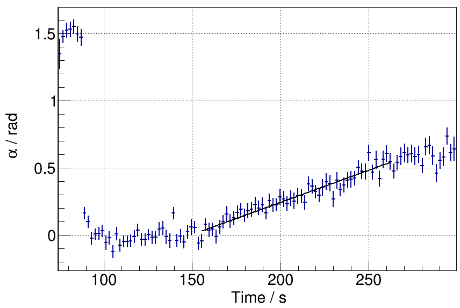
Table 1: Relevant parameters for the deuteron EDM experiment at COSY.

deuteron momentum	p	$0.970\,\mathrm{GeV/c}$
rel. velocity	β	0.459
Lorentz Factor	γ	1.126
gyromagnetic anomaly	G	≈ -0.143
spin tune	ν_s	≈ -0.16
revolution frequency	f_{COSY}	$752\,543\,\mathrm{Hz}$
precession frequency	f_s	$121\,173\,\mathrm{Hz}$
cycle length	T	$270\,\mathrm{s}$ and $450\,\mathrm{s}$
RF Wien Filter	f_{WF}	$872\,949\,\mathrm{Hz}$

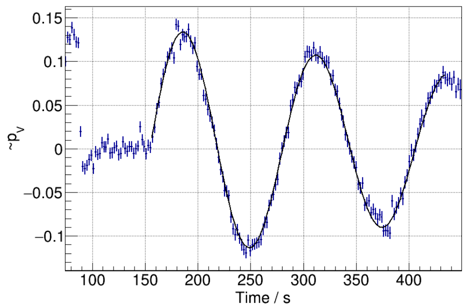
2.1 Invariant Spin axis at the rf Wien filter

In total three different maps were measured during the first Precursor run in 2018. During the experiment only a single bunch was used, which means that the initial slope was used to determine the resonance strength ε. During Precursor Run II, in total 7 maps were taken. During the first two maps the slope technique from Precursor I was repeated. The remaining maps were measured with the oscillation of the vertical polarization.

An example of both methods can be seen in Figure 1(a) (Slope) and 1(b) (Oscillation). In both depicted cycles the vertically polarized beam is rotated into the horizontal plane with an rf solenoid at around $t = 90\,\mathrm{s}$. The spins of the particle bunch start to rotate around the invariant spin axis with $f_s = G\gamma f_{\mathrm{COSY}}$. After switching on the Sibirian snake (and the 2MV Cooler solenoid for one of the maps) this precession is measured and used by the phase feedback to adjust the frequency of the rf Wien filter f_{WF}. At $t = 155\,\mathrm{s}$ the rf Wien filter is turned on, and the vertical polarization starts to build-up (slope method) or oscillate



(a) Slope



(b) Oscillation

Figure 1: Angle between the vertical and horizontal polarization component $\alpha = \arctan(p_V/p_H)$ (left) and vertical polarization (right) as a function of time. The vertically polarized beam is rotated into the horizontal plane at $t = 90\,\mathrm{s}$. When Siberian snake and rf Wien filter are switched on at $t = 155\,\mathrm{s}$, the angle accumulates linearly (left) or the vertical polarization oscillates (right), depending on the method.

(pilot-bunch method). Figure 2 shows an example fit to determine the resonance strength ε from the maximum slope according to Eq. (3) in Sect. 1. For the pilot-bunch technique ε is determined directly by fitting the oscillation frequency of the vertical polarization.

Example plots of the resonance strength ε as a function of the rotation angles ϕ^{WF} (Wien filter) and ξ^{Sol} (Sibirian Snake) are shown in Fig. 3(a) (Slope) and 3(b) (Oscillation). To determine the orientation of the invariant spin axis at the rf Wien filter, the maps are fitted with Eq. (2). A summary of the current status of the orientation of the invariant spin axis for Precursor I and Precursor II is shown in Fig. 4(a) (ϕ_0^{WF}) and 4(b) (ξ_0^{Sol}).

The main challenge understanding these results is their magnitude. Both longitudinal and radial projections are in the order of a few mrad, which is too large to be reproduced by simulations. In Figure 5 a spin tracking simulation of a resonance map is shown including all known misalignments and properties of COSY. The predicted order of magnitude of the orientation of the invariant spin axis is an order of magnitude smaller than in the actual experiment. In addition, we see a sign change in the longitudinal tilt from Precursor I to Precursor II. The reason for this change of sign is still under investigation. One probable reason is the different orbit and, thus, the different imperfection fields probed.

2.2 Longitudinal component of the invariant spin axis ($\vec{n}_z$) at the Siberian snake and the 2 MV Cooler Solenoid

By using solenoids in the ring, the spin of a particle is rotated around the longitudinal axis by an angle χ each turn. Therefore, also the spin tune is modulated by the solenoids. It

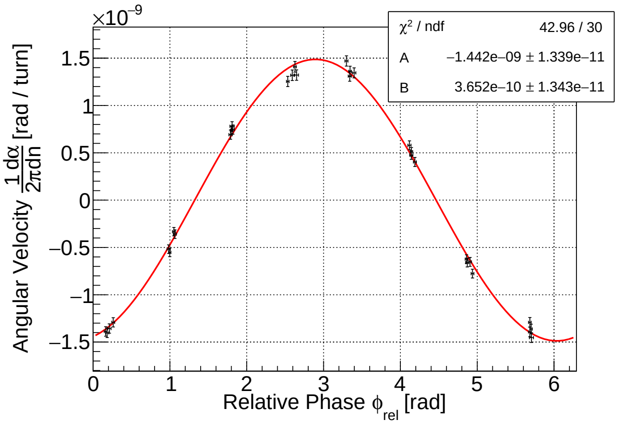


Figure 2: Sinusoidal dependence of the linear build up as a function of the relative phase $\phi_{\text{rel.}}$ according to Equation (3). The amplitude of the sinusoidal fit function corresponds to the resonance strength ε. All measurements are done with $\phi^{\text{WF}} = 0.945\,\text{mrad}$ and $\xi^{\text{Sol}} = 0\,\text{mrad}$.

can be shown that the change of spin tune with respect to the unperturbed spin tune ν_s in the presence of two solenoids in the ring is given by (see [10])

$$\Delta\nu_s = \frac{1}{-\pi}\left[\cot(\pi\nu_s)\left(\cos\left(\frac{k_1 I_1}{2}\right)\cos\left(\frac{k_2 I_2}{2}\right) - 1\right) - n_{z,\text{Sol}}\sin\left(\frac{k_1 I_1}{2}\right)\cos\left(\frac{k_2 I_2}{2}\right)\right.$$
$$\left. - n_{z,\text{Snake}}\sin\left(\frac{k_2 I_2}{2}\right)\cos\left(\frac{k_1 I_1}{2}\right) - \frac{1}{\sin\pi\nu_s}\sin\left(\frac{k_1 I_1}{2}\right)\sin\left(\frac{k_2 I_2}{2}\right)\right], \tag{4}$$

where I_1 and I_2 denote the applied currents to the 2MV Solenoid and the Siberian snake. The calibration factors k_1 and k_2 are used to translate the applied current to spin kick angles and ν_s denotes the unperturbed spin tune. Eq. (4) allows to directly determine the longitudinal component of the invariant spin axis at the 2MV Solenoid and the Siberian Snake by using $n_{\text{z, sol}}$ and $n_{\text{z, Snake}}$ as fit parameters. The change of spin tune $\Delta\nu$ with respect to the unperturbed spin tune as a function of the applied currents to the 2 MV solenoid and the Siberian snake is shown in Fig. 6(b) along with a fit according to Eq. (4) for Precursor II. The longitudinal projections at the solenoids read according to the fit

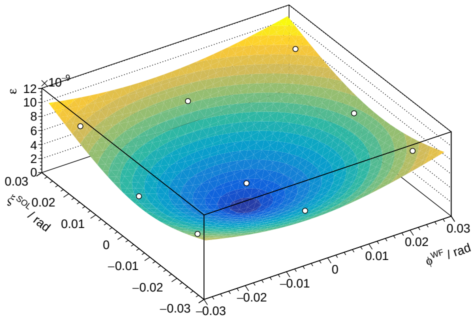
$$n_{z,\text{Snake}} = -5.64(9) \times 10^{-5}\,\text{rad} \tag{5}$$
$$n_{z,\text{Sol}} = -7.03(5) \times 10^{-5}\,\text{rad} \tag{6}$$

During Precursor I, only the Siberian snake was used which reduces Equation (4) to

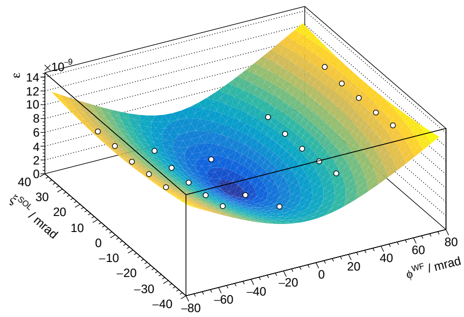
$$\Delta\nu_s = \frac{1}{-\pi}\left[\cot(\pi\nu_s)\left(\cos\left(\frac{kI}{2}\right) - 1\right) - n_{z,\text{Snake}}\sin\left(\frac{kI}{2}\right)\right]. \tag{7}$$

The change of spin tune as a function of current in the Siberian snake is shown in Fig. 6(a) for Precursor I. The longitudinal component of the invariant spin axis at the Siberian snake is given by

$$n_{z,\text{Snake}} = 6.49(2) \times 10^{-4}\,\text{rad}. \tag{8}$$



(a) Slope



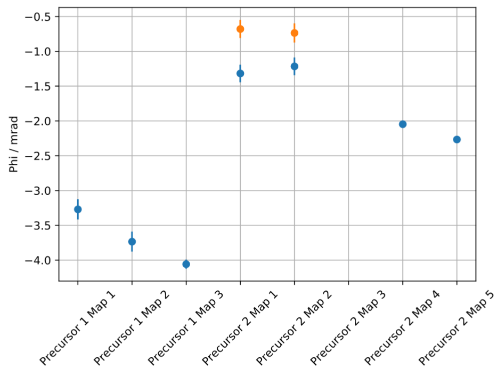
(b) Oscillation

Figure 3: The resonance strength ε as a function of rf Wien filter rotation angle ϕ^{WF} and spin flip angle inside the Siberian snake ξ^{Sol}. The left panel shows a map, where the initial slope technique is used. The right panel shows a map where the pilot bunch technique is used. The minimum of the surface gives the orientation of the invariant spin axis in radial and longitudinal direction.

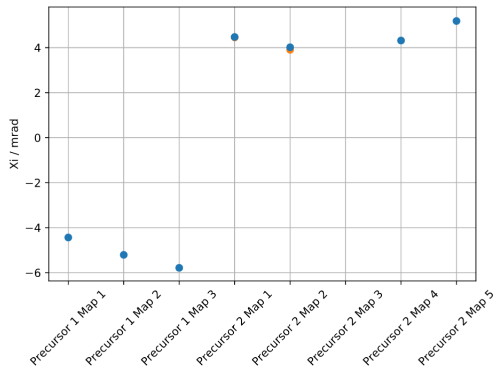
The most striking observation is, that the longitudinal projection of the invariant spin axis measured by this method is up to two orders of magnitude smaller than what we measure using the rf Wien filter. While for the Sibirian snake, which is located in the opposite straight (see Fig. 7), this could be explained by additional spin rotations in the arc, this is especially surprising for the 2 MV Cooler solenoid as this is located close to the RF Wien filter in the same straight. The reason for this mismatch remains unknown and is part of our studies in the upcoming beam time.

It is worth mentioning that the order of magnitude of $n_{z,\mathrm{Snake}}$ decreases by an order of magnitude from Precursor I to Precursor II. As for an ideal ring no tilt of $\vec{n}$ is expected, the reason for this improvement is most certainly the alignment campaigns of the Siberian snake and the other COSY components as well as the beam based alignment.

There is one caveat on Eqs. (4) and (7): they are only applicable for an ideal ring and perfectly aligned solenoids. If the beam and/or the solenoid are misaligned (individually as well as with respect to each other) $\vec{n}_z$ is biased and a correction is non-trivial. As discussed above, during Precursor run I the Siberian snake was not aligned. The same applies to the 2MV Cooler solenoid during Precursor run II. Therefore, we propose to measure this misalignment as we did for the Sibirian snake (see Sect. 5).



(a) ϕ_0^{WF}



(b) ξ_0^{Sol}

Figure 4: Overview of the current status of all measured maps during Precursor I & II. The left panel shows the radial and the right panel shows the longitudinal component component of the invariant spin axis and the position of the rf Wien filter. The two difference colors for Precursor II Map 1 & 2 represent the two bunches.

3 Mapping Field Imperfections using Orbit Measurements

Orbit deviations have to be investigated and understood with ultra-high precision for an EDM measurement to suppress systematic contributions to spin rotation. Thus, false signal contributions to the EDM measurement mainly came from field overlap of nearby magnets leading to a change of the effective length of main dipole magnets. In addition, misalignments of all magnets have to be taken into account to describe orbit deviations. The orbit also depends on the Betatron tune. Both, the orbit deviation and optical setting of the storage ring must be explored in great detail to correct systematics of an EDM measurement. In the next order, also multipole field of magnets have to be investigated.

As a diagnostics tool, the orbit-response matrix (ORM) method can be used. It can be obtained by measuring the closed orbit deviation generated by an individual excitation of correction dipoles. Therefore, the ORM studies for EDM measurements are essential to verify simulation model predictions und improve the understanding of beam dynamics in a storage ring.

The following measurements are proposed:

- Measurement of the ORM for the uncorrected orbit at injection energy of COSY and the beam momentum for the precursor measurement at 970 MeV/c. The measurement of the ORM for the uncorrected orbit eliminates the uncertainties of the calibration of the correction dipoles (steerer magnets) and facilitates the comparison with the COSY model.
- Another relevant correlations are relative orbit changes due to the main dipole field, *i.e.* measurement of the orbit for several, slightly different field values without fur-

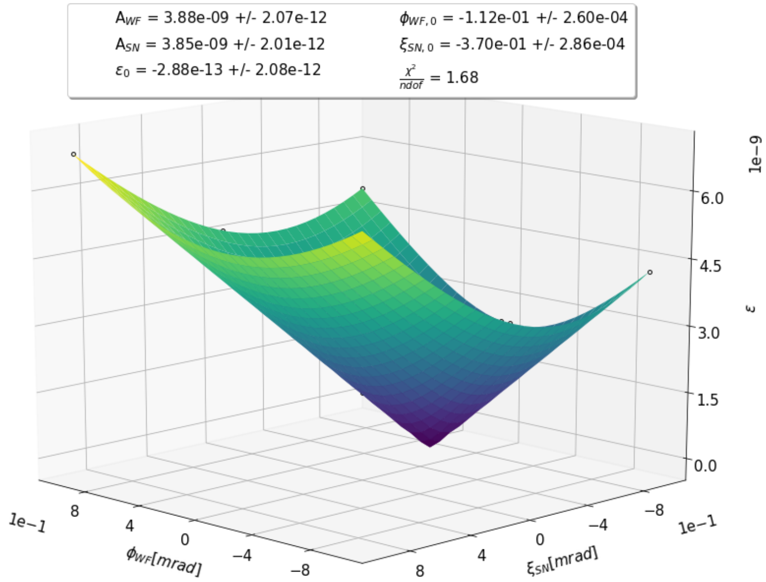


Figure 5: Spin tracking simulations of the experiment including the COSY setup to the best of our knowledge. The orientation of the invariant spin axis is in the order of $0.1\,\mathrm{mrad}$ which is an order of magnitude smaller than in the experiment.

ther changes of COSY. Again, comparisons with the COSY model can lead to its improvement and verify the linearity of COSY.

- The next step is to measure the effect of the correction dipoles for each field setting, *i.e.* basically an ORM measurement for each field setting. However, for comparisons with the simulation, the actual orbit for each steering setting must also be available.
- If additional time is available, other COSY parameters for the ORM measurements can also be changed (e.g., transverse Betatron tunes and chromaticities).

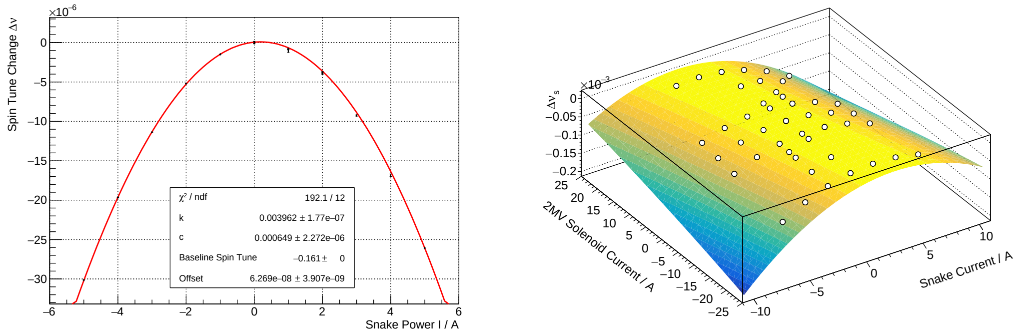
It is important to monitor and record all relevant COSY parameters during ORM measurements to be able to compare the results with the COSY model later.

The measurements proposed here lead to an improved description of COSY and eventually to a better understanding of the precursor experiment in COSY.

These measurements are a prerequisite to finally understand the tilt of the invariant spin axis and connects the results of this chapter to the investigations proposed in the other chapters of this application.

4 Wien Filter Studies

As discussed in Sec. 2, in the precursor runs we measure the direction of the invariant spin axis by aligning the MDM rotation axis with the invariant spin axis. In this configuration,



(a) Precursor I

(b) Precursor II

Figure 6: The change of spin tune $\Delta\nu_s$ with respect to the unperturbed spin tune ν_s as a function of the applied currents to the Siberian Snake and 2 MV Solenoid along with a fit according to Eq. (4) for Precursor I & II.

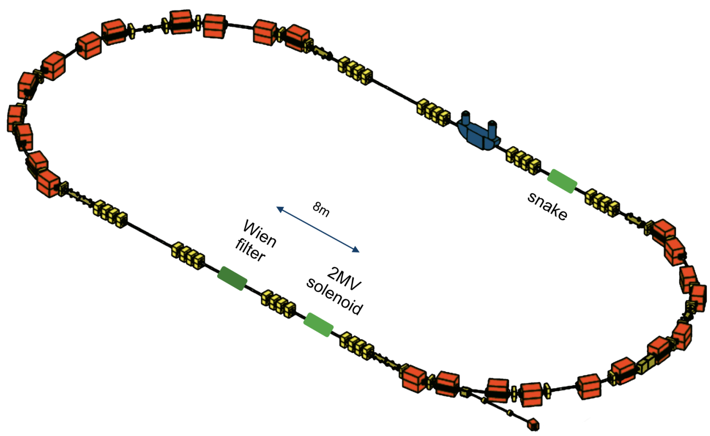


Figure 7: Layout of COSY with the three devices of interest: the RF Wien filter and the 2MV Solenoid in one straight and the Sibirian Snake in the opposite straight.

no spin rotation from the in-plane precession into vertical direction can be observed. For an ideal Wien filter the direction of the MDM rotation axis matches the direction of the magnetic field axis and points into vertical direction. In general, the axis is defined by the geometric design of the Wien filter and its operation parameters. While detailed simulations of the Wien filter show that the uncertainty in the field directions ($\vec{B}$ and $\vec{E}$) are well below a tenth of a mrad [11–13], we would like to confirm this experimentally.

In the actual precursor experiments with polarized beam and a matched Wien filter (*i.e.* with a vanishing Lorentz force) the Wien filter has no effect on the orbit. A slight mismatch would result in coherent beam oscillations at the operation frequency of the Wien filter, here typically about $871\,\mathrm{kHz}$. We measured these oscillations and found amplitudes in the order of $1\,\mu\mathrm{m}$ [14]. In this proposal we want to use a different approach by deliberately

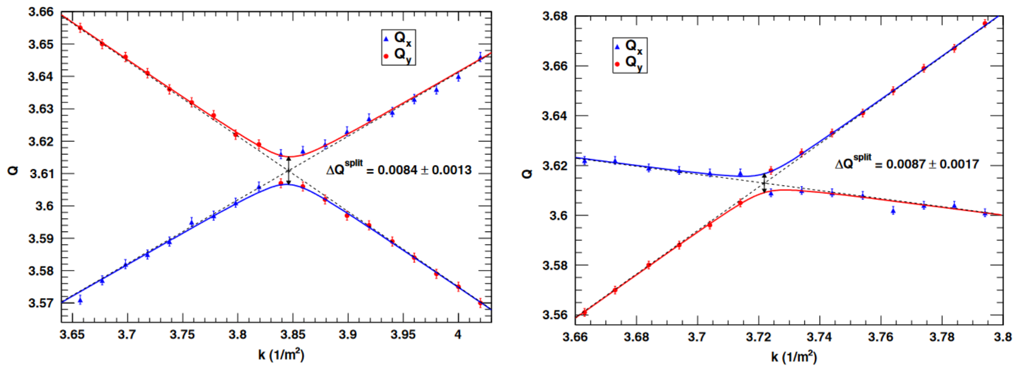


Figure 8: Betatron tunes Q_x (horizontal) and Q_y (vertical) as a function of the focusing strength k_x and k_y, respectively, for the inner (left panel) and outer (right panel) pair of quadrupoles in the PAX low-β section. The data were fitted with a hyperbola. (Picture taken from [15]).

detuning the Wien filter and using the resulting Lorentz force to determine the axis of the combined $\vec{B}$ and $\vec{E}$ fields.

For these studies, the rf Wien filter will be operated in quasi-static mode, *i.e.* with an oscillation frequency equal to the revolution frequency. In this mode, any detuning of the Wien filter generates a constant momentum kick at each time the bunch passes through. Consequently, the Wien filter acts like a horizontal and/or vertical steerer depending on the direction of the field axes, which can then be determined by orbit measurements. If, for example, we put the Wien filter in 0° mode (magnetic field axis vertical), the momentum kick should only effect the horizontal plane. Any unknown transverse tilt of this axis would show up as orbit change in the vertical plane.

There is, however, one effect which can mimic such an observation, namely phase-space coupling. Even when operating COSY without dedicated solenoid fields, the multipoles from dipoles, quadrupoles and sextupole can also contain longitudinal fields inducing phase-space coupling. As discussed in [15] such coupling can be measured using the tune split $\Delta Q^{\text{split}} = Q_x - Q_y$. For this, the horizontal and vertical betatron tune has to be measured as function of quadrupole strength k as shown in Fig. 8. In order to correlate the measured momentum kick with the phase-space coupling and the observed tune split one can use the existing solenoids (snake, $2\,\mathrm{MV}$ cooler) for calibration.

In addition, we would like to study the influence of a non-aligned orbit in the Wien filter. For this, the momentum kicks as function of the beam direction in a tuned (matched) Wien filter will be measured.

5 Alignment of the 2MV cooler Solenoid

During the 2018 Precursor I beam time, the Siberian snake steered the beam because the solenoid magnet was not perfectly aligned with the beam axis. Therefore, in November 2020 an alignment campaign was carried out. The beam path through the snake was slightly varied by changing the vertical and horizontal offset and angle and the change of vertical and horizontal orbit RMS before and after ramping the snake was recorded. In Figure 9 this is shown for the variation of the horizontal angle through. After a few iterations, the optimal beam path through the snake was found and the snake was aligned accordingly (see Table 2). After alignment, the orbit RMS change improved by a factor of 10 (see Table 3) [16]. Besides reducing systematic uncertainties by orbit changes for the Wien filter measurements, this is also important for the determination of the longitudinal component invariant spin axis $n_{z,\mathrm{Snake}}$ at the Siberian snake as Equation (4) assumes, that the magnetic field of the solenoid and the beam path through the solenoid is parallel.

Table 2: Alignment of the Siberian snake (see [16]).

	Horizontal	Vertical
Rotation	$-0.1445°$	$0.1051°$
Translation	$1.385\,\mathrm{mm}$	$-0.27\,\mathrm{mm}$

Table 3: Changes of the orbit RMS in horizontal and vertical direction before and after ramping the Siberian snake to $15\,\mathrm{A}$. After aligning the snake to the magnetic axis of COSY, the change of orbit RMS approaches the same level as having no Siberian snake at all [16].

	Orbit Difference RMS	
	Horizontal	Vertical
With Siberian snake before alignment	$0.351\,\mathrm{mm}$	$0.337\,\mathrm{mm}$
With Siberian snake after alignment	$0.037\,\mathrm{mm}$	$0.020\,\mathrm{mm}$
Siberian snake off, only COSY	$0.022\,\mathrm{mm}$	$0.009\,\mathrm{mm}$

During the Precursor Run II (2021), also the 2MV Cooler Solenoid was used to determine the longitudinal component of the invariant spin axis at the 2MV Solenoid $n_{z,\mathrm{Sol}}$. The solenoid steered the beam in a similar way as the Siberian snake in 2018, which means that the beam path and magnetic field are not aligned. The change of horizontal orbit RMS before and after switching on the solenoids as a function of 2MV Cooler Solenoid current and Siberian snake current is shown in Figure 10. While the Siberian snake has no influence on the orbit RMS, a linear dependence can be seen when changing the 2MV Solenoid current. The change of horizontal orbit RMS means that $n_{z,\mathrm{Sol}}$ shown in Section 2.2 needs to be corrected. To correct this bias, the magnetic field direction of the 2MV Cooler solenoid needs to be known, which can be measured the same way as the alignment of the Siberian snake.

6 Measurement of natural chromaticity

After injection and acceleration of the beam at COSY, the originally vertical polarization is rotated to the horizontal plane by means of a resonant RF solenoid. The survival of the in-plane polarization depends on the spin tune spread that leads to a decoherence of

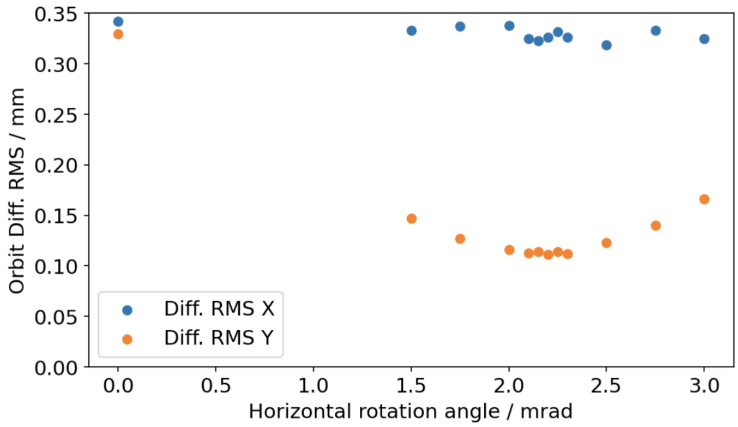


Figure 9: Changes of the orbit RMS difference in vertical and horizontal direction before and after switching on the Siberian snake to $15\,\mathrm{A}$ as a function of horizontal rotation angle through the Siberian snake. By varying the horizontal angle, the orbit RMS differences approach a minimum at around $2.2\,\mathrm{mrad}$ [16].

the spins of the particles. This effect reduces the available observation time for the polarization build-up as an EDM signature. An appropriate model of COSY is essential to determine the conditions under which the rates of spin phase accumulation are the same for all particles (and thus the decoherence is minimal).

Correcting for chromaticities and the second-order momentum compaction factor reduces the path lengthening for particles that do not have the same momentum as the reference particle. This effectively brings all particles to the same orbital length and spin tune. To suppress the spin-tune spread at COSY, we developed a scheme using three families of chromatic sextupoles. For deuterons, the results with the longest in-plane polarization lifetime were obtained when both the vertical and horizontal chromaticities vanish.

To measure the chromaticity for a specific setting of sextupoles, we produced a frequency jump by varying the frequency of the cavity RF. The momentum of the beam is then shifted as

$$\frac{\Delta p}{p} = \frac{1}{\eta}\frac{\Delta f}{f} \tag{9}$$

where η is a slip factor. The shift of the betatron tune relative to the change of momentum then gives the value of chromaticity.

During the measurements of chromaticity, we found that the values of the vertical and horizontal chromaticities without sextupole correction have opposite signs, as given by the constant parameter of linear fit, $\xi_x = -14.91$, $\xi_y = 9.8$, in Figure 11. This is contrary to the ideal model of COSY, where the chromaticities without any sextupole correction are both negative ($\xi_x = -4.54$, $\xi_y = -3.75$), since they are defined by the values of the natural chromaticity. This means that nonlinear fields in COSY, as generated by higher order gradients of the field in dipoles or quadrupoles, contribute significantly to the measured chromaticity. To quantify such effects and compare them with the model, we propose to

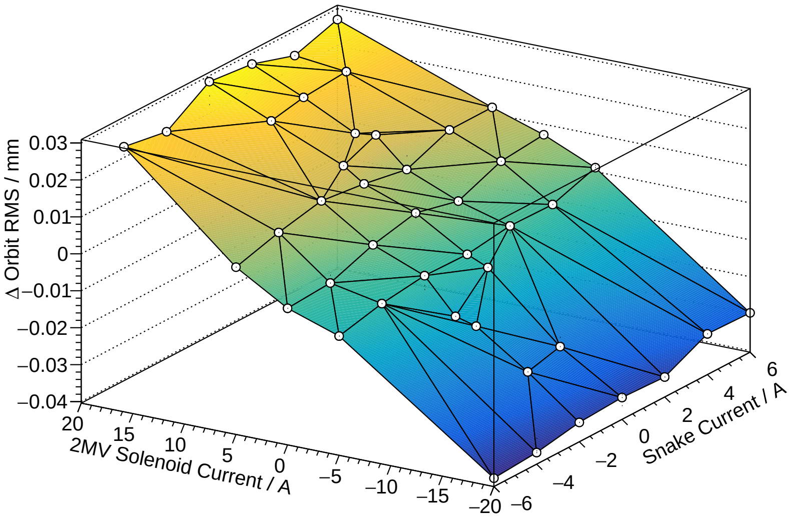


Figure 10: The change of horizontal orbit RMS before and after switching on the solenoids as a function of 2MV Cooler Solenoid current and Siberian snake current. While the change of orbit RMS is unaffected when changing the Siberian snake current, the 2MV Cooler solenoid changes it drastically.

measure the natural chromaticity (which is independent of these effects) so that it can be separated from the total chromaticity.

Natural chromaticity occurs due to change of quadrupole strength with beam energy

$$\xi^x_{\text{nat}} = -\frac{1}{4\pi}\sum \beta_x k_x L_{\text{quad}} \tag{10}$$

$$\xi^y_{\text{nat}} = \frac{1}{4\pi}\sum \beta_y k_y L_{\text{quad}} \tag{11}$$

where $k_{x,y}$ and L_{quad} denote the strength and length of the quadrupole and $\beta_{x,y}$ is the beta-function at the location of the quadrupole (the sum runs over all quadrupoles). If the rf frequency of the cavity and the magnetic field in the dipoles are varied according to

$$\frac{\Delta f}{f} = \frac{1}{\gamma^2}\frac{\Delta B}{B}, \tag{12}$$

the momentum of the bunched beam changes as

$$\frac{\Delta p}{p} = \frac{\Delta B}{B} \tag{13}$$

but it stays on the same closed orbit.

If there is no coupling, this is equivalent to changing the normalized field strength of the focusing magnets. For the central orbit, the result is a tune change proportional to the momentum change, which is the measure of the derivative of the tunes with respect to momentum, with no effect from nonlinear magnetic fields. In this way, we obtain the natural chromaticity of the linear machine without any correction and without the effects of nonlinear fields. These effects are responsible for the discrepancy between the measured chromaticity with sextupoles off and the model.

The method developed and used so far to measure chromaticities at COSY assumes a bunched beam. We propose two different ways to perform the measurement of natural chromaticity:

(i) Using existing methods and tools for data acquisition. A continuous frequency ramp for 2 seconds should be superimposed with a simultaneous dipole B-field ramp. Care should be taken to keep the orbit fixed during the measurement.

(ii) Setting up a B- and f-jump at the flat top of the beam cycle and measuring the tunes before and after the jump. Controlling the orbit deviations should be easier in this case.

The tune measurement requires transverse heating of the beam.

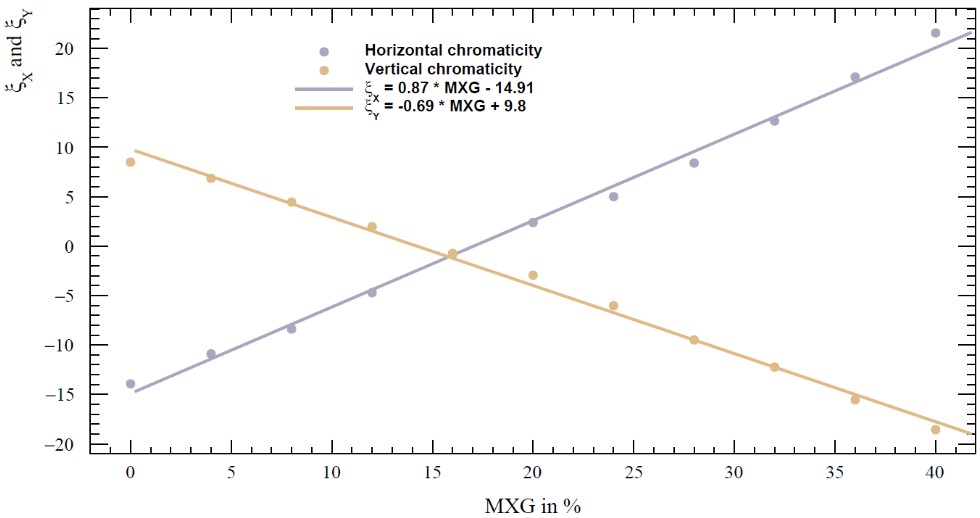


Figure 11: Measurements of horizontal (ξ_x, blue) and vertical (ξ_y, orange) chromaticities for different setting of MXG sextupole family. Lines are linear fits to the points.

7 Beam request

The following table contains an overview over the proposed studies together with the estimated beam time needed (beam preparation and machine developement not included).

Topic	**Tasks**	**Estimated Beam Time**
Orbit studies	Setup and preparation of tools	2 days
	Measurements at injection energy	1 day
	Measurements at $970\,\mathrm{MeV/c}$	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**

In order to perform these systematic studies, we request 2 weeks of deuteron beam with a momentum of $p = 970\ \mathrm{MeV/c}$ in the next scheduling period (part of the measurements will be performed at injection energy). As special equipment we need the $100\,\mathrm{kV}$ electron cooler, the solenoid of the $2\,\mathrm{MeV}$ cooler, the Siberian snake and the Wien filter.

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