COSY Beam Time Request

For Lab. use

Exp. No.:	Session No.
E 005.5	**8**

Collaboration: **JEDI**

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

Jülich, 13.06.2018

Spokespersons for the beam time: **Ralf Gebel (Jülich)**
Alexander Nass (Jülich)
Frank Rathmann (Jülich)

Spokespersons for the collaboration: **Paolo Lenisa (Ferrara)**
Jörg Pretz (Aachen/Jülich)

Address:
Institut für Kernphysik
Forschungszentrum Jülich
52428 Jülich
Germany

Phone: **+49 2461 61 4558** Fax: **+49 2461 61 3930** E-mail: **r.gebel@fz-juelich.de**
a.nass@fz-juelich.de
f.rathmann@fz-juelich.de

lenisa@fe.infn.it
pretz@physik.rwth-aachen.de

Total number of particles and type of beam (p, d, polarization)	Kinetic energy (MeV)	Intensity or internal reaction rate (particles per second)	
		minimum needed	maximum useful
Polarized deuterons	**~970 MeV/c**	**stored ~10^9**	**stored ~10^{10}**
Experimental area	Safety aspects (if any)	Earliest date of installation	Total beam time (No. of shifts)
WASA detector, RF Wien filter, electron cooler, RF solenoid, Siberian snake	**none**	**November 1, 2018**	**2 MD + 4 weeks**

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

The JEDI collaboration

June 20, 2018

Abstract

The JEDI collaboration would like to request beam time for a first deuteron EDM measurement later in 2018. The allocated beam time in May 2018, which was originally foreseen for *First exploratory deuteron EDM experiments with the waveguide RF Wien Filter* (proposal `E005.4`), could only partially make use of polarized beam. During the earlier run in January 2018 (proposal `E005.3`), we could not work with polarized beam at all, because the polarized source became available only late during the run.

For the first deuteron EDM measurement with the RF Wien filter set up without ferrites, **we would like to request 2 weeks of machine development time and 4 weeks of measurement time**, to be tentatively scheduled at the end of the 4$^{\text{th}}$ quarter 2018 (November/December).

Contents

1 Commissioning beam times 5

2 Status of Wien filter commissioning effort 6
2.1 Overview 6
2.2 Driving circuit 7
2.3 Characterization of phase and impedance mismatch 7
2.4 Beam oscillation amplitude induced by mismatched Wien filter 7
2.4.1 Variation of the β-functions at the RF Wien filter at $f_{\mathrm{WF}} =$ 871 kHz 8
2.4.2 Beam oscillation amplitudes at $f_{\mathrm{WF}} = 630$, 1380, and 1621 kHz 9

3 Other improvements 10
3.1 Machine setup 10
3.2 WASA Polarimeter 10
3.3 Additional items 11

4 EDM-like vertical polarization build-up 11
4.1 Theoretical expectations for the buildup in an ideal ring 11
4.2 First measurement of EDM signals 12

5 Beam request 13

1 Commissioning beam times

- In 2017 (proposal **`E005.2`**, November 5 to December 4, 2017), only the last of the foreseen three weeks of beam time could make use of polarized beam.
  - The polarized source became available only late during the run due to problems with the Cs oven.
  - In addition, the extraction septum of the cyclotron had to be replaced.
  - Some data were taken on the out-of-plane spin rotation angles, as described in Sec. 4.2.
- During the run at the beginning of this year (proposal **`E005.3`**, January 21 to February 18, 2018), we did not work with polarized beam at all. Instead, we focused on the commissioning of the RF Wien filter at the different harmonics of the spin-precession frequency.
  - It proved particularly time-consuming to determine the effect of the local variation of the β-functions at the RF Wien filter (using the PAX low-β section) on the magnitude of the resulting Lorentz forces. Preliminary results from these investigations are presented in Sec. 2.4.2.
- During the beam time in May 2018 (proposal **`E005.4`**, May 05 to June 10, 2018), initially intended to be used for *First exploratory deuteron EDM experiments with the waveguide RF Wien Filter*, similar difficulties as in the previous runs delayed the use of the polarized source.
  - Mainly the last week of the beam time (just ended on June 11, 2018) was successfully used to test, for the first time, the interplay of all sub-systems of the experiment.
  - As a major machine development item, a new mode of operation for COSY was established that allows us to switch off not only the electron beam on flattop, but all magnetic elements of the 100 keV cooler altogether. In addition, on flattop the magnitude of the strong steerer fields in the cooler section were reduced to $\approx 5\%$ of the nominal value.
    - The new operation mode simplifies the COSY lattice substantially, and as a result, spin-tracking simulations shall become simpler.
  - During the last three days of the run, some data on the EDM-like vertical polarization buildup signal were collected for different spin-rotation angles, for the first time using the Siberian snake, together with a variation of the rotation angle of the RF Wien filter around the beam axis.
- For the time being, we consider the commissioning of the RF Wien filter *without* ferrites completed.
  - The collaboration decided to install the ferrites at the RF Wien filter only after a conclusive first measurement of the deuteron EDM has been

obtained. The ferrites for the RF Wien filter[1] are available and can be installed at any time.

- **The beam time requested with the present proposal shall be used for a first production run to determine the deuteron EDM.**

2 Status of Wien filter commissioning effort

2.1 Overview

- The RF Wien filter is fully operational with a total power of up to $P = 1.5\,\mathrm{kW}$, fully sufficient for a first direct EDM measurement.
  - Higher RF power by about a factor of 2.5 is possible with the presently used four RF amplifiers.
  - Beyond that, another factor of 2 in power becomes available, when eight instead of the presently used four slaves are employed.
- All four feedback loops for the stable operation of the RF Wien filter have been tested and are operational.
  - **Loop 1:** Locks the relative phase of the RF of the Wien filter with respect to the in-plane polarization.
  - **Loop 2:** Minimizes the Lorentz force $\vec{F}_{\mathrm{L}}$, exerted on the beam at the four harmonics of the spin frequencies [1]:

$$\begin{aligned} K &= -1 : 871\,\mathrm{kHz}\,, & K &= +1 : 630\,\mathrm{kHz}\,, \\ K &= -2 : 1621\,\mathrm{kHz}\,, & K &= +2 : 1380\,\mathrm{kHz}\,. \end{aligned} \tag{1}$$

  - **Loop 3:** Minimizes the phase between the E and B fields inside the Wien filter.
  - **Loop 4:** Keeps the horizontal and vertical beam position stable at the entrance and exit of the beam in the RF Wien filter.
- The remote rotation of the RF Wien filter around the longitudinal axis from the experiment control at COSY Warte for small angles of $\pm 5°$ has been implemented in the Lab View control system.
  - Electronic levels[2] are used to set the rotation with a precision of at least $170\,\mathrm{\mu rad}$.

[1]manufactured by National Magnetics Group, Inc. http://www.magneticsgroup.com/.

[2]ZEROTRONIC inclination sensor, WYLER AG, Winterthur, Switzerland https://www.wylerag.com.

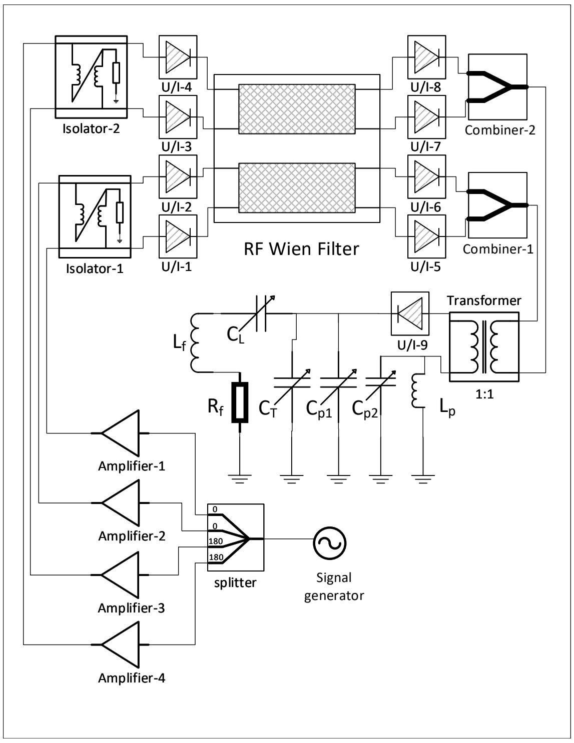


Figure 1: Driving circuit of the RF Wien filter. In the present setup of the experiment without ferrites, the variable capacitances C_{L} and C_{T} are used to match the Wien filter (C_{p1} and C_{p2} are not sensitive), *i.e.*, minimize the Lorentz force $\vec{F}_{\mathrm{L}}$ and the E to B phase. Matching at the different harmonics requires the exchange of the fixed inductance L_{f}.

2.2 Driving circuit

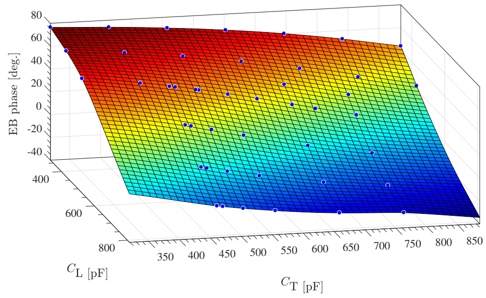
The driving circuit, shown in Fig. 1, allows us to operate the RF Wien filter at the four harmonics, listed in Eq. (1). Switching from one harmonic frequency to another requires the exchange of the fixed inductance L_{f}. The variable elements C_{L}, C_{T}, C_{p1}, and C_{p2} are used to match the Wien filter, *i.e.*, they minimize the Lorentz force $\vec{F}_{\mathrm{L}}$ and the E to B phase.

2.3 Characterization of phase and impedance mismatch

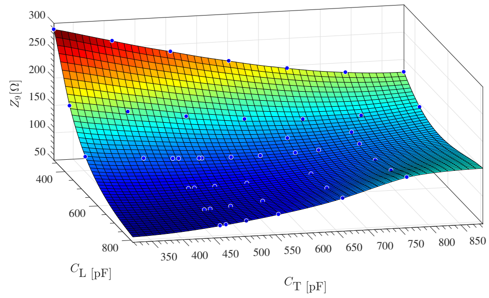
For $f_{\mathrm{WF}} = 871\,\mathrm{kHz}$, the E to B Phase and impedance Z_9 as function of the capacitances C_{L} and C_{T} are shown as an example in Fig. 2. C_{L} and C_{T} are varied in steps from 0 to 10000. A step size of 1 corresponds to $\Delta C_{\mathrm{L}} = \Delta C_{\mathrm{T}} = 6.8 \times 10^{-2}\,\mathrm{pF}$.

2.4 Beam oscillation amplitude induced by mismatched Wien filter

The vertical beam oscillation amplitudes ε_y, generated by the RF Wien filter, when there is an E to B impedance or phase mismatch have been determined via the



(a) Phase between electric field E and magnetic field B in the RF Wien filter as function of C_L and C_T.



(b) Impedance Z_9 as function of C_L and C_T. $Z_9 = 79\,\Omega$ when matched to the deuteron momentum of $970\,\mathrm{MeV/c}$.

Figure 2: Panel (a) E to B phase, and (b) impedance Z_9 at $f_{WF} = 871\,\mathrm{kHz}$.

detection of the coherent beam oscillations using the COSY BPM #17[3], located behind the last ring dipole in front of the WASA detector. During these measurements, the magnetic field of the RF Wien filter pointed sideways (along x), thus the induced Lorentz force $\vec{F}_L$ pointed along the vertical (y) direction. Care was taken that the horizontal and vertical beam positions at the RF Wien filter did not vary by more than $\Delta x = \Delta y = \pm 0.5\,\mathrm{mm}$ during the measurements.

2.4.1 Variation of the β-functions at the RF Wien filter at $f_{WF} = 871\,\mathrm{kHz}$

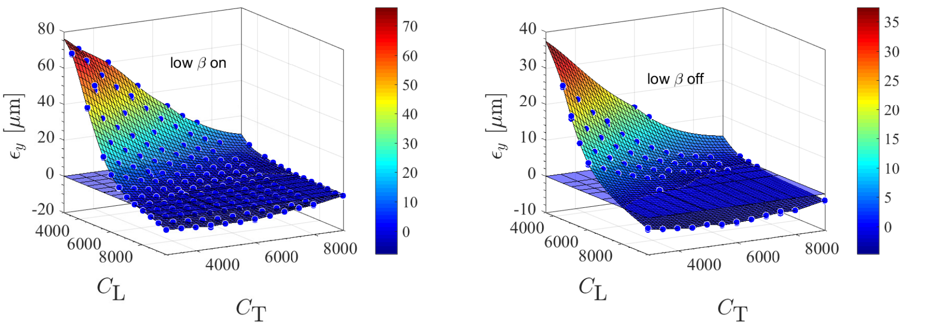
The RF Wien filter has been intentionally set up in the PAX low-β section of COSY in order to be able to vary the amplitude of the β-functions at the Wien filter. For a deuteron momentum of $p = 970\,\mathrm{Mev/c}$, the beta-functions at the center of the RF Wien filter decrease by a factor 3 to 4 when the low-β is switched on (see Table 1).

	Low-β Off	Low-β On
β_x	4 m	1.0 m
β_y	3 m	1.2 m

Table 1: Calculated β-functions using MAD at the center of the RF Wien filter. As in previous measurements, these values possess uncertainties of about 10% [3].

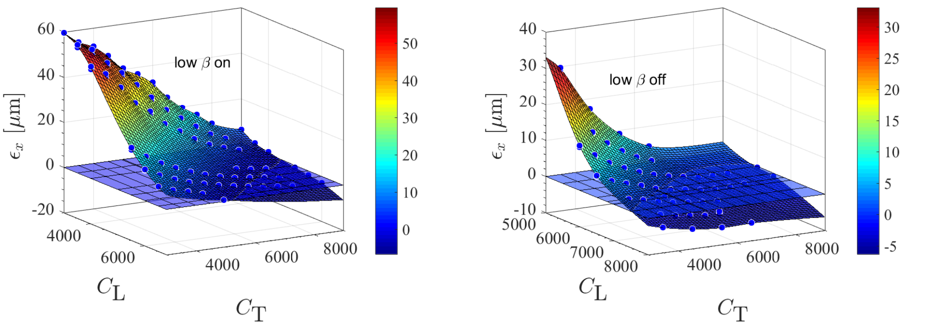
The amplitudes of the vertical beam oscillations were measured during the January 2018 beam time. The results, shown in Fig. 3, indicate that when the low-β section is turned on, for the same settings of the driving circuit, the induced beam oscillations become substantially larger. Although, as discussed in [1], this behavior is expected, single-pass calculations did not allow us to quantify the effect. Beam tracking simulations using realistic time-dependent fields of the RF Wien filter are not yet available.

[3]A previous study [2] had shown that this choice provides a good compromise between x and y sensitivities in a single BPM.



(a) Low-β section ON.

(b) Low-β section OFF.



(c) Low-β section ON.

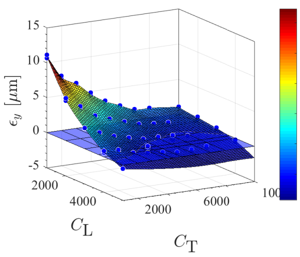
(d) Low-β section OFF.

Figure 3: $f_{\mathrm{WF}} = 871\,\mathrm{kHz}$, RF power $P = 1\,\mathrm{kW}$, the matching point is at $C_{\mathrm{L}} = 6800$ and $C_{\mathrm{T}} = 4950$: Panel (a) shows the vertical beam oscillation amplitudes ε_y measured using BPM #17 for low-β section ON, and panel (b) for OFF. Panels (c) and (d) show the corresponding horizontal beam oscillation amplitudes ε_x. The driving circuit uses a fixed $L = 28\,\mu\mathrm{H}$, and the matching point (E and B in phase and Lorentz force $\vec{F}_{\mathrm{L}} = 0$) is given. C_{L} and C_{T} are set in steps from 0 to 10000, the capacitances range from 50 to 950 pF for this circuit setup.

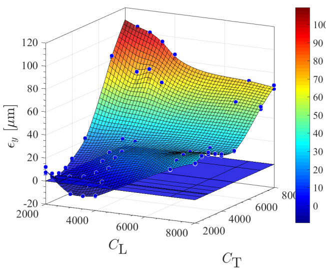
2.4.2 Beam oscillation amplitudes at $f_{\mathrm{WF}} = 630$, 1380, and $1621\,\mathrm{kHz}$

When the RF Wien filter is operated at the $K = +2$ harmonic of the spin-precession frequency, the magnitudes of ε_y are quite similar to the ones at $K = -1$, as shown in Figs. 3(b) and 4(b). At the other harmonics $K = +1$ and -2, however, the oscillations induced in the beam appear to be smaller by about a factor of five (compare Figs. 4(a) or 4(c) with Fig. 4(b)).

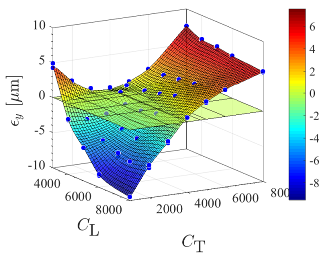
Since the magnitudes of the beam oscillations that are generated by the RF Wien filter are related to the accumulated magnetic moment rotations in the machine, the systematics of an EDM measurement will depend on the chosen Wien filter harmonic. Therefore, the EDM measurements should eventually be carried out at all available harmonics, because each of these measurements will receive a different contribution to the systematic error from ε_y. In addition, the experimental results on ε_y will provide an excellent testing ground for future beam (and spin-)tracking calculations.



(a) $f_{\mathrm{WF}} = 630\,\mathrm{kHz}$: Fixed $L_{\mathrm{f}} = 30\,\mu\mathrm{H}$. Capacitances range from 500 pF to 1.5 nF. Matching point at: $C_{\mathrm{L}} = 4400$ and $C_{\mathrm{T}} = 3700$.



(b) $f_{\mathrm{WF}} = 1380\,\mathrm{kHz}$: Fixed $L_{\mathrm{f}} = 25\,\mu\mathrm{H}$. Capacitances range from 50 pF to 950 pF. Matching point at: $C_{\mathrm{L}} = 2450$ and $C_{\mathrm{T}} = 2980$.



(c) $f_{\mathrm{WF}} = 1621\,\mathrm{kHz}$: Fixed $L_{\mathrm{f}} = 20\,\mu\mathrm{H}$. Capacitances range from 50 pF to 950 pF. Matching point at: $C_{\mathrm{L}} = 3200$ and $C_{\mathrm{T}} = 4700$.

Figure 4: Vertical beam oscillation amplitudes ε_y as function of C_{L} and C_{T} for the other three harmonics of the spin-precession frequency for low-β section off. An RF power of 1 kW has been applied, and for all points shown, E and B are adjusted to be in phase.

3 Other improvements

Below, various other improvements to the experimental setup and the procedures involved have been implemented.

3.1 Machine setup

- The automatic COSY orbit control with the Schneider box feedback to stabilize the detector rate ran reliably in both the horizontal and vertical ring planes toward the end of the May '18 run.

- Progress was made with beam-based alignment at COSY. The purpose of these investigations is to better characterize the real position offsets of the BPMs installed at COSY. Based on a first test of beam-based alignment using quadrupole QT12, recently carried out at COSY, a dedicated proposal has just been submitted for the next session of the CBAC [4].

3.2 WASA Polarimeter

1. The previous commissioning times were successfully used to make the WASA detector available as on-line polarimeter for polarization monitoring, spin tune measurement and phase-locking.

2. The carbon block target at WASA is routinely operated. The orbit control in conjunction with the vertical target position and the extraction process have been optimized.

3. During the November '17 and May '18 commissioning runs, improved versions of the phase-lock feedback have been tested with polarized beam.

3.3 Additional items

Several additional items have been addressed during the previous commissioning runs.

1. Read-back of dipole, steerer, quadrupole, sextupole, and solenoid currents has been implemented at COSY. The data are stored in the EPICS database, including the settings of the Schneider box, and the active spin bits from the polarized ion source.

2. Two more Zurich lock-in amplifiers[4] have been implemented for the Lorentz force measurement, now making use of only BPM #17, and the signals from the four BPM quadrants are acquired individually.

3. A 10 MHz frequency reference signal has been prepared and is distributed to the COSY RF, the solenoid RF, and the Wien filter RF, in order to make sure that all frequency generators agree frequency-wise.

4. The Wien filter has been aligned with respect to the COSY ring plane which was determined during the recent COSY magnet survey.

   - When the RF Wien filter is aligned with respect to the COSY ring plane, the electronic levels at the RF Wien filter for vertical and horizontal $\vec{B}$ fields read:

$$\begin{aligned} &\#3483\text{Z:} \quad \theta(\vec{B} \parallel \vec{e}_y) = (+0.74 \pm 0.17)\,\text{mrad at } T = 21.006\,^\circ\text{C} \\ &\#3486\text{Z:} \quad \theta(\vec{B} \parallel \vec{e}_x) = (+0.57 \pm 0.17)\,\text{mrad at } T = 20.865\,^\circ\text{C}\,, \end{aligned} \tag{2}$$

   and here $\vec{e}_y$ denotes the true normal to the ring plane, and $\vec{e}_x$ is a radially-outward pointing vector in the ring plane.

5. An improved calibration of a new pair of Rogowski coil BPMs is presently being established using an upgraded laboratory test setup. The calibrated coils will be installed at the entrance and exit of RF Wien filter during the fall shutdown in September/October 2018.

4 EDM-like vertical polarization build-up

4.1 Theoretical expectations for the buildup in an ideal ring

The basics of the operation of the RF Wien filter have been worked out in the JEDI publication on the spin tune mapping technique [5]. The quantitative interpretation

[4] Zurich Instruments, Zurich, Switzerland, model HF2LI, https://www.zhinst.com/products/hf2li.

of the initial slope of the vertical polarization $\dot{S}_y$, which in the absence of machine imperfections is strictly proportional to the EDM, depends on the relative orientation of the Wien Filter axis and the stable-spin axis in the COSY ring (see Eqs. (A9), (A7), (A10) of Appendix A of [5]).

As discussed in the recent JEDI publication [6], the rate of change of the out-of-plane rotation angle

$$\dot{\alpha}(t) = \frac{\mathrm{d}}{\mathrm{d}t}\left[\arctan\left(\frac{p_y(t)\cdot \bar{A}_y}{p_{xz}(t)\cdot \bar{A}_y}\right)\right] , \tag{3}$$

is well-suited to quantify the effects due to the EDM and the machine imperfections. The azimuthal orientation of the RF Wien filter, $\phi^{\mathrm{WF}}_{\mathrm{rot}}$, can be controlled mechanically by a rotation of the device around the beam direction.

The direction of the stable-spin axis can be manipulated by static solenoids in the ring. For the latter purpose, as explained in [5], in the past, the compensation solenoids of the 100 keV electron cooler were employed. During the May 2018 commissioning run, we made use for the first time of the Siberian snake, installed between the ANKE dipole magnets D1 and D3 in the straight section opposite to the RF Wien filter. The Siberian snake is well-aligned with respect to the beam. Furthermore, much larger solenoid fields can be applied in a more symmetric fashion than previously possible [5, Table I].

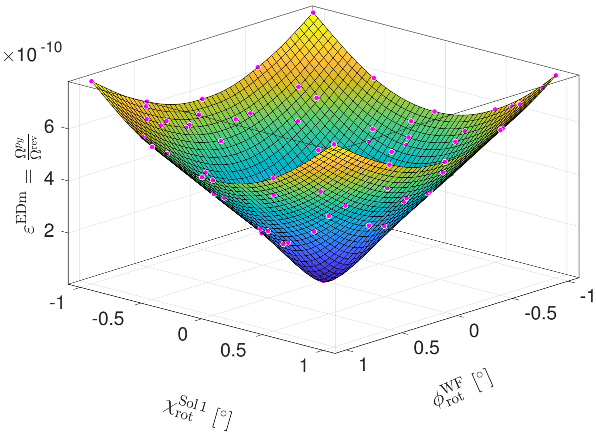
The EDM resonance strength $\varepsilon^{\mathrm{EDM}}$, actually a *resonance tune* (in analogy to the machine and spin tunes), can be conveniently defined as the ratio of the angular frequency of the vertical polarization oscillations Ω^{p_y}, induced by the EDM relative to the orbital angular frequency Ω^{rev},

$$\varepsilon^{\mathrm{EDM}} = \frac{\Omega^{p_y}}{\Omega^{\mathrm{rev}}} . \tag{4}$$

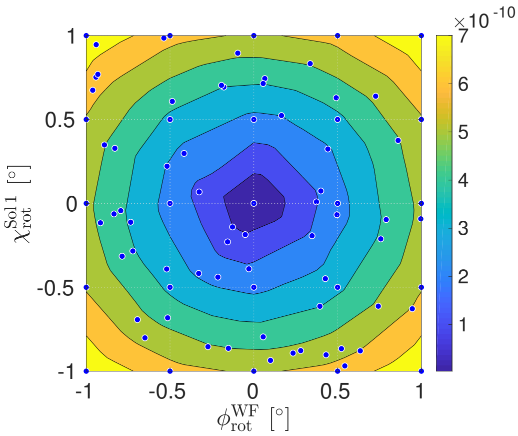
A COSY-like model ring is used to numerically simulate the effects in an ideal ring that contains an ideal RF Wien filter in one straight section, operated at an RF power of $P = 1\,\mathrm{kW}$, and a solenoidal magnet in the opposite straight section. In Fig. 5, the resulting resonance strengths $\varepsilon^{\mathrm{EDM}}$ are plotted as function of $\phi^{\mathrm{WF}}_{\mathrm{rot}}$ and $\chi^{\mathrm{Sol\,1}}_{\mathrm{rot}}$ for a $\pm 1^\circ$ interval.

4.2 First measurement of EDM signals

The goal of the beam time requested with this proposal is to obtain a map of the resonance strength similar to the one shown Fig. 5. Available at this point in time are only very few measurements of the polarization buildup from the November '17 (and the May '18) runs with the magnetic field of the Wien filter oriented along the vertical (y) direction, *i.e.*, along the normal to the ring plane. We need substantially more data to be able to quantify the systematic effects of the EDM measurement. Figure 6 shows this data set of measurements for $\dot{\alpha}$ as function of the relative phase between deuteron spin and Wien filter RF for different azimuthal rotation angles of the RF Wien filter $\phi^{\mathrm{WF}}_{\mathrm{rot}}$ and spin rotation angles $\chi^{\mathrm{Sol\,1}}_{\mathrm{rot}}$.



(a) 3D graph of the resonance strength $\varepsilon^{\rm EDM}$.



(b) Contour plot of (a).

Figure 5: Simulated resonance strength $\varepsilon^{\rm EDM}$, as defined in Eq. (4), on a regular 5×5 point grid, plus 64 random grid points in the range $\phi^{\rm WF}_{\rm rot} = [-1, \ldots, +1]^\circ$ and $\chi^{\rm Sol\,1}_{\rm rot} = [-1, \ldots, +1]^\circ$.

Variations of $\phi^{\rm WF}_{\rm rot}$ and $\chi^{\rm Sol\,1}_{\rm rot}$ do affect the axis around which the deuteron spins rotate which leads to different patterns of phase motions, as shown in Fig. 6, and a corresponding extension of the formalism developed in [5] is in progress.

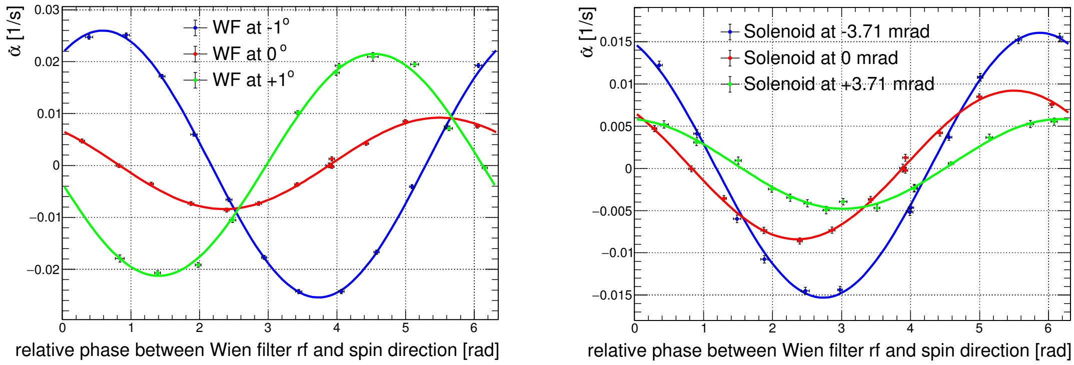
5 Beam request

Now, that the commissioning of the RF Wien filter for the four available harmonics of the spin-precession frequency for the experimental setup without ferrites is accomplished, the JEDI collaboration would like to request beam time to collect a statistically and systematically meaningful data sample. Given the experience from the previous commissioning runs, this particular experiment requires longer setup times than usual, and therefore **we request for the first deuteron EDM measurement with the RF Wien filter 2 weeks of machine development time and 4 weeks of measurement time**, to be tentatively scheduled at the end of the 4$^{\rm th}$ quarter 2018 (November/December).

References

[1] J. Slim, R. Gebel, D. Heberling, F. Hinder, D. Hölscher, A. Lehrach, B. Lorentz, S. Mey, A. Nass, F. Rathmann, *et al.*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **828**, 116 (2016), http://www.sciencedirect.com/science/article/pii/S0168900216303710.

[2] V. Schmidt, *Simulation of mismatched Wien filter fields and the effect on the closed-orbit at COSY* (2017), JEDI Internal Note, available from http://collaborations.fz-juelich.de/ikp/jedi/private_files/



(a) $\dot{\alpha}$ for the Wien filter rotation angles $\phi_{\text{rot}}^{\text{WF}} = -1$, 0, and $+1°$ around the beam axis and the cooler solenoid turned off ($\chi_{\text{rot}}^{\text{Sol 1}} = 0$).

(b) $\dot{\alpha}$ for the cooler solenoid spin rotation angles $\chi_{\text{rot}}^{\text{Sol 1}} = -1$, 0, $+1°$ and $\phi_{\text{rot}}^{\text{WF}} = 0$.

Figure 6: Rate of out-of-plane rotation angle $\dot{\alpha}$ as function of the Wien filter RF phase, when the magnetic field of the RF Wien filter is oriented normal to the ring plane, and the Wien filter is operated at $f_{\text{WF}} = 871\,\text{kHz}$. Panel (a) shows Wien filter rotations while the solenoid is set to 0, panel (b) shows different solenoid spin rotation angles when the Wien filter is at 0°.

intnotes/WF_kick.pdf, http://collaborations.fz-juelich.de/ikp/jedi/private_files/intnotes/WF_kick.pdf.

[3] C. Weidemann, F. Rathmann, H. J. Stein, B. Lorentz, Z. Bagdasarian, L. Barion, S. Barsov, U. Bechstedt, S. Bertelli, D. Chiladze, *et al.*, Phys. Rev. ST Accel. Beams **18**, 020101 (Feb 2015), http://link.aps.org/doi/10.1103/PhysRevSTAB.18.020101.

[4] T. Wagner and B. Lorentz, *Beam-based alignment* (2018), available from http://collaborations.fz-juelich.de/ikp/jedi/public_files/proposals/Proposal_Beam_Based_Alignment_short.pdf.

[5] A. Saleev, N. N. Nikolaev, F. Rathmann, W. Augustyniak, Z. Bagdasarian, M. Bai, L. Barion, M. Berz, S. Chekmenev, G. Ciullo, *et al.* (JEDI collaboration), Phys. Rev. Accel. Beams **20**, 072801 (Jul 2017), https://link.aps.org/doi/10.1103/PhysRevAccelBeams.20.072801.

[6] N. Hempelmann, V. Hejny, J. Pretz, H. Soltner, W. Augustyniak, Z. Bagdasarian, M. Bai, L. Barion, M. Berz, S. Chekmenev, *et al.* (JEDI Collaboration), Phys. Rev. Accel. Beams **21**, 042002 (Apr 2018), https://link.aps.org/doi/10.1103/PhysRevAccelBeams.21.042002.