COSY Beam Time Request

For Lab. use

Exp. No.:	Session No.
E 005.6	**11**

Collaboration: **JEDI**

An improved pilot bunch-based spin phase-lock feedback system for the measurement of the deuteron electric dipole moment

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Total number of particles and type of beam (p, d, polarization)	Kinetic energy (MeV)	Intensity or internal reaction rate (particles per second) minimum needed	Intensity or internal reaction rate (particles per second) 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	**none**	**September 1, 2020**	**1 MD + 1 week**

An improved pilot bunch-based spin phase-lock feedback system for the measurement of the deuteron electric dipole moment

The JEDI collaboration

December 5, 2019

Abstract

The JEDI collaboration would like to request a beam time to test an improved spin phase-lock feedback system. This will allow, for the first time, the direct measurement of deuteron electric dipole moment using the frequency of oscillation the vertical polarization P_y instead of only using the initial slope of P_y. Consequently, upon success, the EDM resonance strength could be mapped out as a function of the Wien filter phase and solenoid field.

For this investigation **we would like to request 1 week of machine development time and 1 week of measurement time**, to be tentatively scheduled at the end of the 3rd quarter 2020 (September).

1 Commissioning the waveguide RF Wien filter

- The RF Wien filter is fully operational with a total power of up to $P = 1.5\,\text{kW}$, fully sufficient to perform a first direct EDM measurement.
  - Higher RF power levels by about a factor of 2.5 are achievable with the presently used four RF amplifiers.
  - Beyond that, another factor of 2 in RF 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 [3]:

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

  - **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 $\pm 5^\circ$ has been implemented in the Lab View control system.
  - Electronic levels[1] are used to set the rotation of the RF Wien filter around the beam axis with a precision of at least 170 µrad.

2 An improved spin lock feedback system

2.1 Motivation

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It was noticed during the previous precursor run, that the spin phase-lock feedback looses its track of the spin signal once the spin has been rotated into the vertical direction. Figure 1 shows an example of a polarization build-up excited by the waveguide RF Wien filter running at one of the resonant spin precession harmonics (*i.e.*, 871 kHz). The most important parameter is the slope indicated by the

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

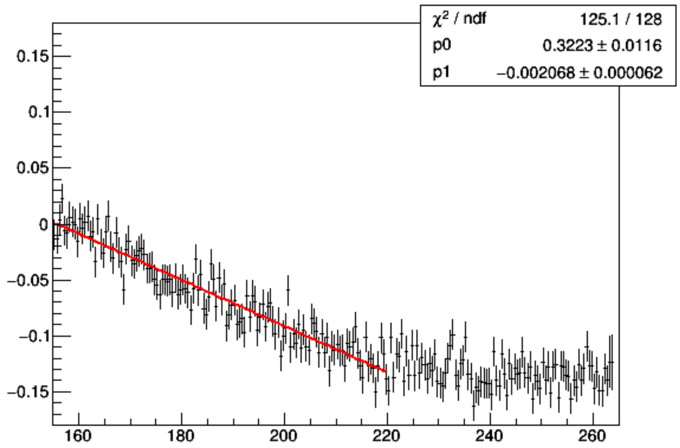


Figure 1: Polarization build-up while running the RF Wien filter on resonance continuously.

red solid line. One can see that the fit starts from nearly 160 s and ends at 200 s that is exactly where the feedback loop (in its current version of implementation) cannot proceed further.

In Fig. 2, we measured the spin precession frequency for a short time and then set the frequency of the Wien filter only once (not continuously, as we did before), an irregularly shaped sinusoidal signals appeared. As a conclusion, it seems that the feedback system is producing undesirable effects on the measurements.

To further understand the effects of the feedback, some simulations have been conducted. The simulation scenario included an RF Wien filter running continuously on resonance. Roughly speaking, this requires measuring the spin tune continuously, *i.e.*, turn-by-turn. The results are shown in Panel (a) of Fig. 3. First of all, one can see that the spin tune values of the extremum range between -0.166 and -0.156, are too large and cannot match the spin precession frequency. Panel (b) elaborates more on these results: taking the moving mean of the data shown on Panel (a), (blue line with the left scale) shows a variation between $-0.161\,15$ and -0.1608. Surprisingly, this corresponds to a frequency variation of the order of 300 Hz, a value that is too

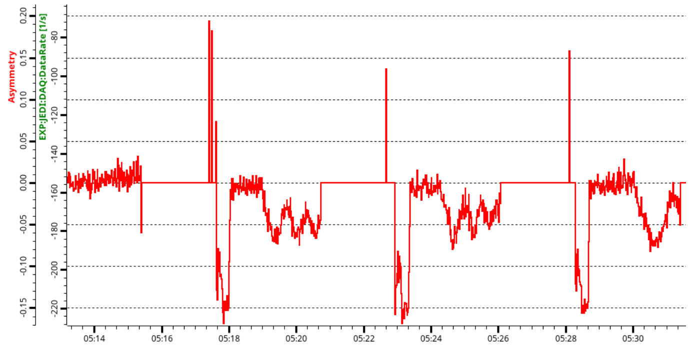
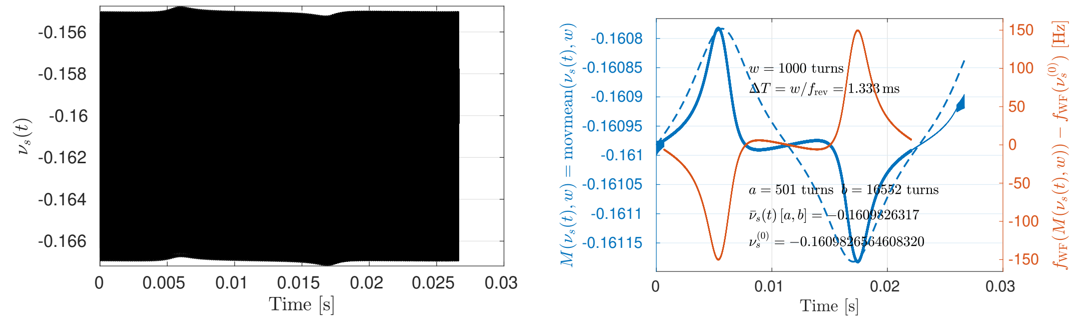


Figure 2: Polarization build-up while g the RF Wien filter without continuous feedback.

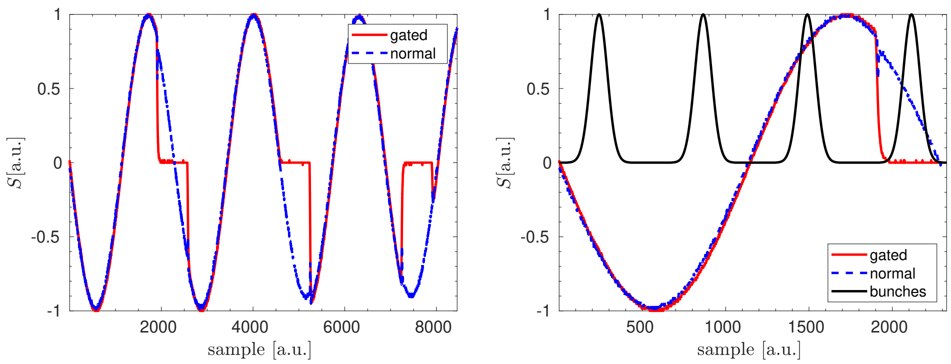
large to be true.



(a) preliminary (b) preliminary

Figure 3: (a): Running spin-tune per turn. (b): Left scale (blue) shows the moving mean of the spin tune while the dashed line is an analytic prediction of the time dependence of the running spin tune scale. The right scale (red) denotes the corresponding running frequency difference [2].

The conclusion is, **when measuring the spin tune, the RF Wien filter should be switched off**, and this shall be tested in the requested beam time. Measuring the *in-plane* spin precession while the fields of the RF Wien filter are oscillating does **not** strictly correspond to the spin tune, but rather to the *running* spin tune.



(a) (b)

Figure 4: (a) Blue: instance of an un-gated signal; red: instance of a gated signal; (b) Blue: one period of an un-gated signal; red: one period of a gated signal; black: four-bunches beam signal

2.2 Proposed solution

To solve this problem, we propose to run the precursor experiment with a multi-bunch beam structure. The COSY group has already successfully operated the machine with four bunches for a complete beam time.

In multi-bunched beam, the fields of the RF Wien filter will be visible to only three of four bunches. This leads to an RF field-free bunch, also known as pilot bunch. The spin tune will be only measured using the pilot bunch. Then, using Loop-1 (see Sec. 1), the feedback system maintains the spin precession frequency and the phase at the RF Wien filter.

To realize the aforementioned idea, the driving circuit of the RF Wien filter is modified to include a gating circuit. The basic idea is to cut off a portion of the wave either that is feeding the amplifiers (small-signal gating) or possibly, the amplified signals (large-signal gating) in a way that at least one bunch does not see the fields of the RF Wien filter. Panel (a) of Fig. 4 shows an example of a gated signal (red graph) and an *unperturbed* one (blue graph). Panel (b) indicates exactly the intended scenario. The requested beam time should achieve that at least one of the four bunches stored in COSY is not affected by the fields of the RF Wien filter.

For the experimental, it is sufficient to run the RF Wien filter in the so-called 90° mode, *i.e.*, vertical electric field and radial magnetic field. In this mode of operation, only vertically polarized beam is required. We would like to obverse driven spin oscillations on all the bunches except the pilot bunch.

The new feedback system shall be used to determine the frequency of the polarization which can be used to determine the EDM resonance strength. Upon success, all four frequencies of the RF Wien filter (Eq. 1) will be tested as well.

3 Status update

3.1 Allocated beam time

The original plan to study the multi-bunch operation of the RF Wien filter during the E005.6 JEDI-experiment, scheduled for week 5 (27.01 - 02.02.2020), cannot be realized. The manufacturer of the components has informed us that there are time delays due to technical difficulties and a change of personnel (for more details, see Sec. 3.2)

During week 5 of 2020, the JEDI collaboration would like to use the beam to implement a new 8-channel RF generator at the RF Wien filter, which will allow us to improve the performance of the device. In addition, we would like to commission a new method for monitoring the matching of the E and B fields by measuring the modulation of the detector rates, resulting from residual beam oscillations at the Wien filter frequency.

The beam time is jointly prepared, organized and carried out together with the JEDI polarimeter experiment E002.7, because both experiments need in-plane polarization with a long spin coherence time. Based on our experience, the preparation for this will take nearly two weeks, which will include a large fraction of the first experimental week 5. The JEDI collaboration therefore would prefer to keep the beam time schedule as is.

3.2 Technical development

Various technical solutions implemented towards the goal of an *in-ring multi-bunch spin manipulation* have been tested. As stated above, the high-power amplifiers used so far, have been designed to operate in the range of 0.1 to 10 MHz. The initial investigations showed that this is not sufficient, when the input signal is gated. The problem arises from mainly harmonic distortions and probably some intermodulation. Higher-bandwidth up to 30 MHz power amplifiers have been tested, and the results were slightly better, but also insufficient to conduct the precursor experiment. Fortunately, the company that fabricated the driving circuit, had an ongoing project to develop a broadband power amplifier up to 200 MHz. The results were remarkably good and possibly sufficient to conduct the experiment. However, the power of this device is limited; they provide a power level of 125 W, which means that the total power in the waveguide RF Wien filter will be limited to 500 W. Higher power levels are possible, but will take some time to develop as the technology is not yet ready.

A second alternative was to use high-power, high-speed RF switches. This constitutes a quite challenging task. A commercial solution does not exist and consequently, this had to be researched. An adequate transistor solution with its own driving circuit has to be developed and implemented. Two solutions have been proposed, namely, optically and magnetically coupled transistors. With the former, the driving circuit of the transistor appears feasible, however, it introduces a delay in the switching on/off processes. A prototype has been developed, but failed to assert the requirements. The second prototype based on the magnetically coupled transis-

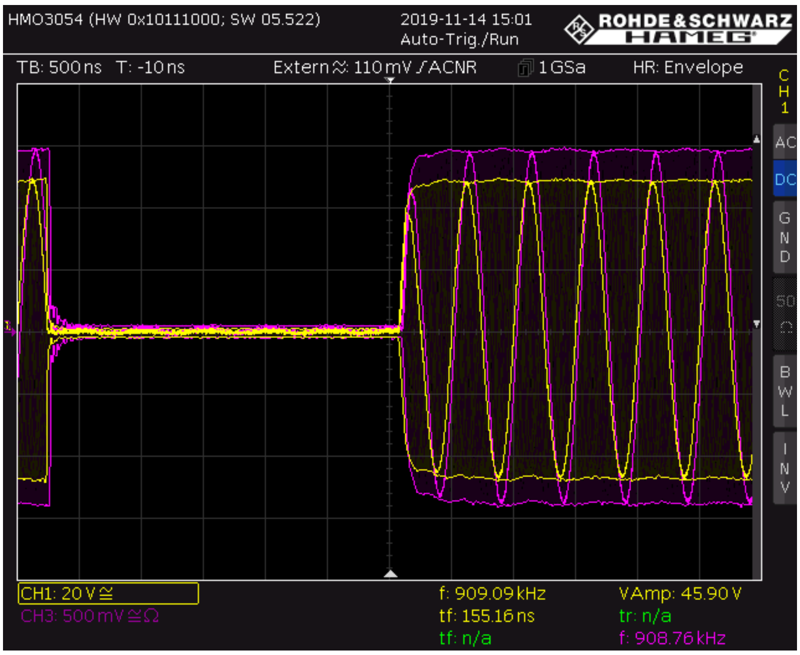


Figure 5: The magenta graph denotes the input signal and the yellow one represents the (damped) output signal. The envelope functions are shown in both cases.

tor showed to be extremely promising. A switching speed of 5 ns could be reached. The schematics are not shown here, only the test results are included in Fig. 5. The magenta graph denotes the input signal and the yellow one represents the output signal. The envelope functions are shown in both cases. One can see clearly that the output signal is following very closely the input. The switching on/off processes work well within the specifications limit.

In the undergoing process, a purely sinusoidal signal will be fed to the *current* power amplifiers. Each switch can handle 250 W, allowing the experiment to run at 1 kW. The remaining problem to be solved is, how to direct the dumped power. A solution has been proposed which requires low-frequency, and high-power circulators [1]. These are also RF components that do not exist yet commercially to the required specifications, and will take some time to develop.

4 Request

For this investigation **we would like to request 1 week of machine development time and 1 week of measurement time**, to be tentatively scheduled at the end of the 3$^{\text{rd}}$ quarter 2020 (September).

References

[1] D. Pozar. *Microwave Engineering*. Wiley, 2004.

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[3] J. Slim, R. Gebel, D. Heberling, F. Hinder, D. Hölscher, A. Lehrach, B. Lorentz, S. Mey, A. Nass, F. Rathmann, L. Reifferscheidt, H. Soltner, H. Straatmann, F. Trinkel, and J. Wolters. Electromagnetic Simulation and Design of a Novel Waveguide {RF} Wien Filter for Electric Dipole Moment Measurements of Protons and Deuterons. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 828:116 – 124, 2016.