COSY Beam Time Request

For Lab. use

Exp. No.: **E3**	Session No. **2**

Collaboration: JEDI

Stabilizing the deuteron spin tune with active feedback

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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	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)
EDDA detector, electron cooler and RF solenoid	**none**	**1st November 2015**	**1 week (+ MD)**

Beam Time Request

Stabilizing the deuteron spin tune with active feedback

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Abstract

We request one week of polarized deuteron beam in 2016 to commission a system that uses information from the continuous, online polarimeter (EDDA) to adjust the phase of the polarization as it rotates in the horizontal plane of the COSY ring. The adjustment is made following a short (1 second) data acquisition time and immediate analysis of these data using as assumed value for the spin tune. From that result, a correction is determined for the phase of the polarization rotation. Then the rf cavity frequency is bumped for a short period of time (< 1 second) to change the beam velocity and the relativistic parameter γ so that the rate of polarization precession changes until the right orientation is obtained. Then additional data is taken and the cycle is repeated. This freezes the phase, in effect demonstrating that such feedback may be used in real time to hold the polarization along the direction of the beam velocity for an EDM experiment with a storage ring.

Introduction

The storage ring search for an electric dipole moment (EDM) requires that the beam polarization be maintained nearly parallel to the beam velocity for times of about 1000 s [2,3]. If the spin tune, $\nu_S = G\gamma$ where *G* is the deuteron anomaly and γ is the relativistic factor, is fixed from the start of beam storage, then it would have to be set with a precision of better than 1 part in 10^{10} if the polarization is not to drift by more than 1 radian from the forward direction during the beam storage time. This is clearly beyond the reach of power supply stability, so the direction of the polarization must be maintained by adjusting a ring parameter such as the rf cavity frequency based on a continuous monitor of the polarization direction. Such stability is also needed for any "precursor" EDM experiments of the "partially frozen spin" variety [4] made with the COSY ring in its present configuration.

The commissioning [5] of a new data acquisition (DAQ) system capable of time-marking and unfolding the precession of the deuteron polarization in the horizontal plane offers the possibility of monitoring the magnitude and phase of the polarization on time scales of one second or less. In addition, the initial phase of the polarization may be set reproducibly to a precision of about 0.2 rad by triggering the rf solenoid system that precesses the polarization into the horizontal plane on a particular phase point in the rf cavity oscillation [5]. Measurements have shown that the phase typically varies slowly (much less than 1 rad/s), so subsequent measurements of the horizontal plane polarization could be used as input to an active correction scheme that would attempt to stabilize the phase measurement with time. For the EDM experiment, there are two goals for the feedback system. The first is to maintain the direction of the polarization in the forward direction. The second, and somewhat more subtle, goal is to adjust the energy of the ring so that there is no tendency for the direction to drift.

The next section describes in more detail how we could achieve feedback stabilization of the spin tune using an extension of the data acquisition system that is presently used for in-plane polarization measurements. Beginning in this way may be the most efficient way to get online, understand the system, and make improvements. It may also be possible to realize such feedback in a more compact and stable system by programming it for an FPGA. This would be a second step in the development. (It will not be discussed further below.)

This beam time request is intended to obtain the priority to begin with the hardware portion of the development for this project. It is expected that we would be ready for the first run in 2016. A deuteron beam is preferred because of the prior success in measuring horizontal deuteron polarization and the slow rate of deuteron polarization precession, which allows an adequate response time with the present data acquisition system.

Description of feedback hardware operation

The key piece of new hardware that is needed is a high precision (9 decimal digits) sine wave generator that may be externally programmed from the DAQ system. This would replace the generator now used for the rf cavity. Generators with this level of precision are presently available as commercial items. It may be possible to find one already equipped with external input, in which case the development reduces to mostly a software issue. Some attention must be paid to the requirements for stability, which may be a temperature- or noise-controlled environment. Another requirement is needed so that changes to the input frequency do not change its phase when a new value is entered. Perhaps the best way to ensure minimal impact on the phase would be to require continuity of the output sine wave across the change.

The currently-used DAQ assigns to each event a clock time (typical period for the run of Ref. [4] was 92 ps). The DAQ also receives a logic pulse from the rf cavity signal once every 100 rf cycles. From this information the data analysis system determines the number of turns (an integer) since an arbitrary $t = 0$ point. Multiplying this number by the spin tune gives the total rotation angle in revolutions of the polarization since $t = 0$. The *fractional* part of this number is used to assign a direction bin to each event from the polarimeter. (For the initial study described in Ref. [4], nine bins were used. This number was large enough to have only a small effect on the magnitude determined while maintaining good statistics in each direction bin.) The down-up asymmetry is calculated from the events recorded in each direction bin based on the azimuthal angle group (left, down, right, and up) assigned by the EDDA scintillators used as the polarimeter [4]. The asymmetries are reproduced by a sinusoidal function as:

$$f(\phi) = A\sin\phi + B\cos\phi + C \tag{1}$$

where ϕ is the angle associated with the direction bin. The magnitude of the sideways asymmetry is $M = \sqrt{A^2 + B^2}$ and the phase is the four-quadrant arc-tangent of A/B. C is an offset that absorbs most of the first-order systematic errors in the measurement. A sample of phases reported in Ref. [4] is shown as Fig. 1.

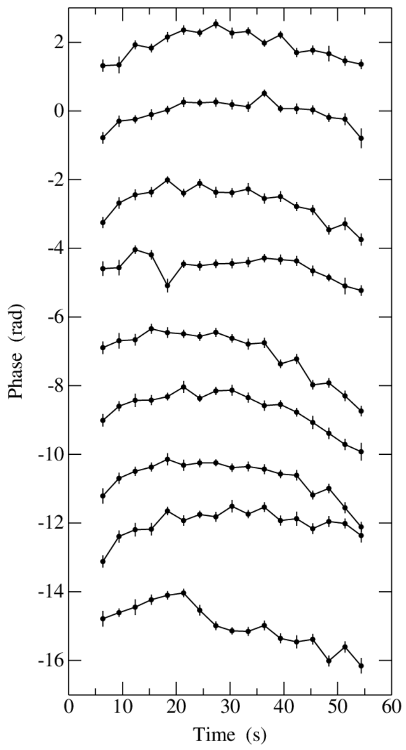

Figure 1: Measurements of the phase on successive beam stores using time bins of 3 seconds with each. Each new storage cycle is displaced by −2 rad from the previous one to allow easy inspection.

These measurement show a generally smooth and slowly varying behavior with time. In many cases the data may be represented by a parabolic function. In such a case the linear term may be interpreted as the error in choosing the original spin tune (which is held constant through the analysis) and the quadratic term is the linear part of the change in spin tune with time. Since these data were taken, the statistics have improved, allowing measurements in 1-second time bins with smaller errors.

The analysis of the data to produce such a plot may be completed in a fraction of the time that it took to acquire the data. Thus real-time feedback based on such an analysis is feasible.

The main correction that is needed is to rotate the polarization in the horizontal plane until it points in the correct direction. With the continuous precession of the polarization (at a rate of about 120 kHz), the equivalent goal is to adjust the system until the phase measurements cluster about a chosen value. In either case, the adjustment consists of a “bump” in the frequency of the rf cavity that lasts for only a short time. This causes the average momentum of the beam to change, and this changes the spin tune through its connection with the relativistic parameter γ. For the typical operation at p = 0.97 GeV/c,

$$\frac{\Delta \nu_S}{\nu_S} = \frac{\Delta \gamma}{\gamma} = \beta^2 \frac{\Delta p}{p} = \beta^2 \eta \frac{\Delta f}{f} \tag{2}$$

where $\beta = 0.46$ is the relativistic velocity fraction, $\eta = 0.612$ is the slip factor, and $f = 750602.5$ Hz is the revolution frequency. For example, a rotation of the polarization direction of 1 radian may be accomplished by shifting the rotation frequency by $\Delta f = 7.7$ Hz for 1 s. The time of these bump operations should be as short as practical consistent with maintaining good machine operation.

Figure 2 is a somewhat exaggerated example of the phases in a beam store [see also Ref. [6]). The top panel is a hypothetical phase history based on a quadratic curve. The initial linear rise represents an "error" in the selection of the spin tune value for use in the analysis. This produces a linear growth in the phase difference from the starting point. In addition there is a large quadratic term that would arise if the spin tune itself is changing linearly with time.

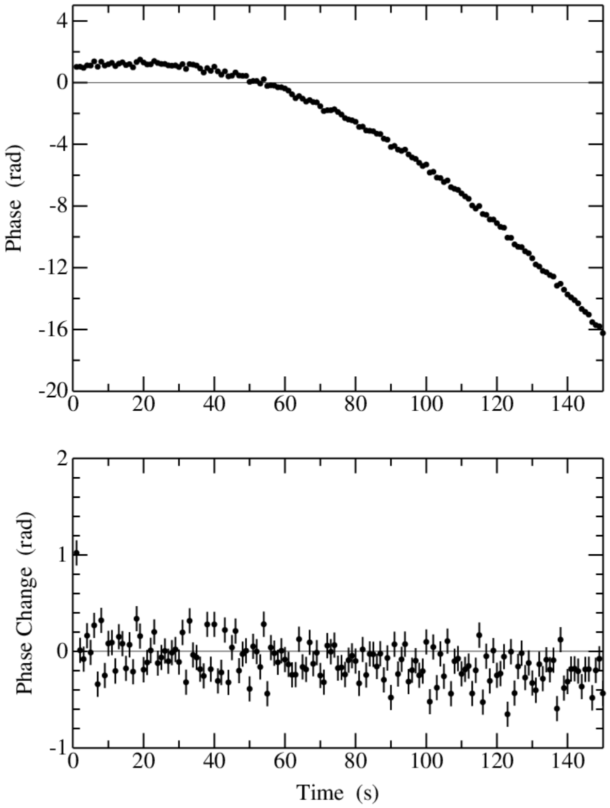

Figure 2: (Top panel) The phase in a hypothetical beam store as it follow a quadratic time trajectory. The imagined data points occur every second. They are given variations about the original curve based on a Gaussian distribution with a sigma width of 0.13 rad. (Bottom panel) The change applied to the horizontal polarization direction in order to bring the measurement in each time bin to zero, the target phase. After each data point, the change is applied to all subsequent points. This graph is also the set of data that would arise if a direction correction is applied following each measurement. The error bar reflects only the statistical error in the phase measurement. By responding to a noisy input, this process effectively increases the scatter in phase measurements.

The lower panel shows the "correction" made by the system at the end of each second. For the first second, the correction is about 1 radian, the displacement in the upper phase curve at that time. Having made that correction, the changes for subsequent seconds are shown. The changes drift downward as the quadratic part of the upper curve starts to dominate. This makes most of the corrections one-sided, a situation that in the real experiment would need attention. Thus this information on spin tune drift is available for study, and models may be developed to compensate for it. Such a model must follow the general trend but not respond to the fluctuations associated with individual uncertainties in each data point. The Fourier transform of such a filter may be adjusted to follow trends at various rates. Any changes would occur in the baseline frequency to which the rf cavity returned following a direction adjustment bump.

In the data acquisition and analysis computer, the data taking/storage task would be independent of the data analysis task, but with access to the same data files. Cross-links would be needed to ensure synchronization of analysis with the changes from one time bin to another. There would be some latency in the analysis and computation of the next bump, and some time required to complete the bump. Thus some time bins would be skipped if they coincided with an analysis operation.

Development and running plan

For the remainder of 2015, we plan to investigate and acquire the hardware needed to implement the high precision signal generator and carry out most of the software work needed to develop a communications protocol and analysis package. This will be built on the work already completed for the analysis of horizontal polarization.

For the initial testing phase, we would like for one week of 0.97 GeV/c vector polarized deuteron beam to be included in the list of requests for 2016. The beam should be bunched and electron cooled. The setup should include adjustment of the sextupole fields in the ring so that the horizontal polarization lifetime is long.

For the running of a partially frozen spin precursor experiment, we would need a second high precision programmable signal generator that would be used to drive the Wien filter. A pickup would send a representative signal from the filter back to the DAQ where it would be time-stamped and processed as any other event stream. In this case, the analysis would only look to determine in which direction bin these events fell so as to monitor the phase with respect to the rotating polarization. A spread of time bins would indicate an incorrect Wien filter frequency. The requirement is that polarization must be along the beam direction when the Wien filter is at a maximum. A slip of 90° would render the system insensitive to any EDM-like effect. The directions may be calibrated against the initial rotation of the polarization into the horizontal plane. If an oscillating field is centered on the spin resonance or one of its harmonics, then the maximal field of the rf solenoid is associated with a fully sideways polarization. Analysis of this data affords a reference for the phase.

References

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