Recent Progress in Polarization Lifetime and Control for an EDM Search with 0.97 GeV/c Deuterons in a Storage Ring

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(Dated: January 31, 2017)

The observation of an electric dipole moment (EDM) or its upper limit at levels near 10^{-29} e·cm would either uncover new forms of CP violation or put at risk many models that seek to explain the excess of matter over anti-matter in the present universe. This talk presents new results on studies of the feasibility of conducting an EDM search using a polarized deuteron beam circulating in a storage ring. In the EDM experiment, the selection of an appropriate match of electric and magnetic bending fields makes possible holding the direction of the polarization always parallel to the momentum. In this configuration, the transverse electric field always present in a storage ring will rotate the polarization into the vertical direction at a rate proportional to any EDM on the deuteron. For this, it is necessary to maintain the polarization for times up to a thousand seconds to allow an opportunity for the EDM signal to become observable despite the instability of this configuration.

A time-marking system for polarimeter events has been installed on the COSY Synchrotron at the Forschungszentrum-Jülich in Germany. The clock time information makes possible the unfolding of the anomalous precession (120 kHz at $p_{\rm d} = 0.97$ GeV/c) so that polarimeter events may be sorted according to the direction of the rotating polarization, assuming a precise value for the precession rate. From this analysis it is possible to measure the magnitude of the in-plane polarization (IPP) as a function of time and determine the rate at which the polarization decoheres. This tool allows the study of ways to lengthen the IPP lifetime even though the polarization direction is not locked to the momentum. A combination of beam bunching, electron cooling, and the adjustment of ring sextupole fields permits the cancellation of decoherence that arises from transverse betatron oscillations in the beam.

This talk will present the most recent results taking advantage of sextupole magnet settings that also give zero chromaticity. From runs made in 2015, it has now been demonstrated that IPP lifetimes can exceed 1000 seconds.

The data acquisition and analysis system also yields the phase (or direction at a particular time) of the rotating IPP. Drifts in the COSY storage ring are slow enough that the phase may be tracked smoothly over many 1-second time bins. This capability now makes it possible to consider using the phase information in a slow feedback stream to the ring rf cavity so that the direction may be made to point in a particular place and held over time. Such a capability is essential for the EDM search. Results will be shown illustrating the operation and calibration of this feedback system. With the use of the rf solenoid in the ring, a mock EDM-type experiment was run in which the solenoid was used to drive a vertical accumulation of the polarization.

I. INTRODUCTION

A storage ring provides a way to confine charged particles and subject them to an electric field for times long enough to observe the precession due to an electric dipole moment (EDM) if one should exist at levels above 10^{-29} e·cm [1]. The precession starts with the beam polarization in the (horizontal) plane of the storage ring and held parallel to the beam velocity ("frozen spin") through the appropriate choice of electric and possibly magnetic confining fields. The electric field in the particle frame is always radial, regardless of its origin, and is perpendicular to the spin direction. Through interaction with the EDM, the slow induced precession will produce a growing vertical polarization component.

Feasibility of the storage ring experiment requires that we demonstrate the ability to retain this in-plane polarization (IPP) for times up to 1000 s and that, through feedback from polarization measurements, it is possible to continually adjust the polarization direction so as to minimize deviations from the direction of the beam velocity. In the COoler-SYnchrotron COSY [2], the combination of electro-magnetic fields needed to keep the polarization and beam velocity parallel does not exist. But methods have been developed to measure the magnitude of the polarization as it rotates (nominally at a rate of 120 kHz) in the ring dipole fields [3] and to know at any time the phase of that rotation. With this IPP as the substitute for frozen spin, it has been shown that a combination of beam bunching, electron cooling, sextupole field adjustment, and limited beam currents can result in an IPP lifetime of at least 1000 s [4]. This contribution will review this result and also present a new demonstration that the precession rate and phase may be adjusted in real time in response to polarization measurements.

II. MEASURING THE MAGNITUDE AND PHASE OF THE IN-PLANE POLARIZATION

In order to follow the rotating IPP, each polarimeter event is marked with a clock time (in steps of 92.6 ps). In parallel, the time of each RF cavity oscillation is sampled and a prescaled version recorded by the data acquisition system. A comparison of these two clocks allows each event to be assigned a turn number since the time of a "$t = 0$" marker set near the beginning of each beam store. The integer part of the turn number is converted into a total precession angle Θ (in revolutions) since $t = 0$ by multiplying by $\nu_S = G\gamma$, the spin tune, where $G = -0.142987$ is the deuteron magnetic anomaly and $\gamma = 1.12583$ is the relativistic factor [5]. The fractional part of Θ is taken to be the phase associated with that particular polarimeter event. All events within a given time interval (*e.g.*, one second) are binned in phase and the down-up asymmetry calculated for each bin. The result varies sinusoidially with phase, and a fit yields the polarization magnitude and time bin phase relative to $t = 0$ (see Fig. 1). Initially the value of γ is not known with enough precision to guarantee a signal, so a short scan around the starting value for the analysis is made until a peak in the magnitude is observed. This is repeated for each time bin in the store. A good set of time bin phases is obtained only after the value of γ is fixed to a reasonable average value. This value becomes the reference point for any future adjustments of the spin tune or phase. Figure 2 shows a sample of the scans for the correct value of spin tune or γ.

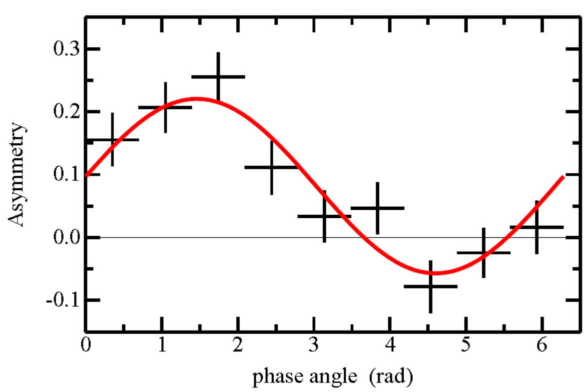

FIG. 1. Down-up asymmetry values measured for a set of nine phase bins, each 40^o wide. The red curve is a best fit using $f(\phi) = 0.2056 \sin(\phi - 0.09636) + 0.06717$.

Good consistency is usually obtained. With a fixed value of γ, the typical time bin phase varies smoothly from bin to bin.

The width of the maximum in Fig. 2 is about 1 ppm of the central value. The typical scatter from time bin to time bin is at the level of 1 part in 10^7.

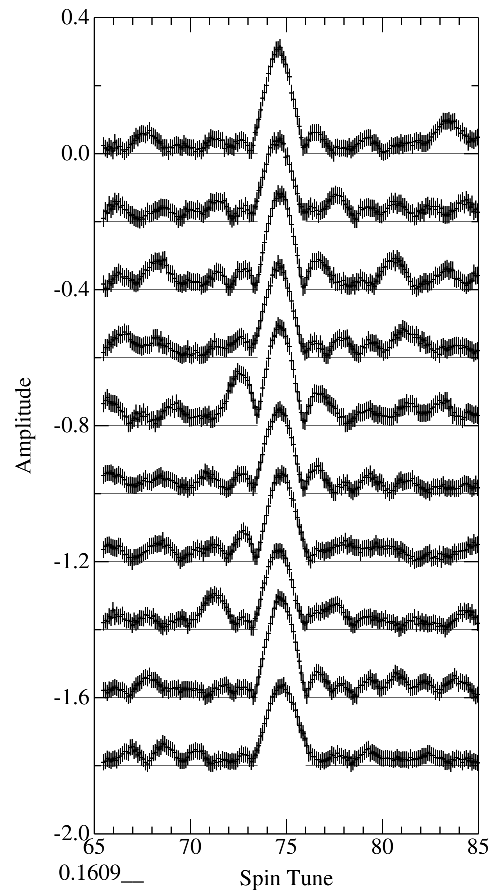

FIG. 2. A series of scans of the fitted magnitude for a series of time bins as a function of the assumed value of the spin tune (note suppressed significant digits). Each scan is shown lower by 0.2 for clarity and represents the results for a 4-s time bin.

III. CONTROLLING PHASE AND SPIN TUNE

For the EDM experiment, the direction of the IPP must be maintained within some tolerance window (perhaps ± 5 deg). Fortunately, the error signal, which is the size of the down-up asymmetry, has a zero at the desired value and varies linearly as the error increases. There will also be occasions during the EDM search when it is necessary to rotate the IPP so that it is fully sideways and measure the magnitude of the polarization. The most convenient way to alter the spin tune is to change γ by changing the revolution frequency of the storage ring. This implies adjustments to the frequency at a level of mHz. Two types of adjustments needed: (1) adjustments to the spin tune made by changing the revolution frequency, and (2) adjustments to the phase (polarization direction) made by applying a revolution frequency change for a limited time and then restoring it.

The connection between spin tune change and revolution frequency is usually given by:

$$\frac{\Delta\nu_S}{\nu_S} = \frac{\Delta\gamma}{\gamma} = \beta^2\frac{\Delta p}{p} = \frac{\beta^2}{\eta}\frac{\Delta f}{f} \tag{1}$$

where $p = 0.970$ GeV/c, $\beta = 0.459$, $\eta = 0.612$, and $f = 750602.5$ Hz [5] The minimum step on the frequency generator input available at COSY is 3.7 mHz, so it is possible to make changes as small as $\Delta f/f = 2 \times 10^{-9}$.

A software capability was added so that commands to change the revolution frequency could be sent by the data acquisition computer and applied immediately to the COSY rf frequency generator. The rf generator provided a transition between the two values that allowed for a match that preserved continuity.

Initial tests sent a new rf frequency value and then, after several seconds, a return to the old value, as shown in Fig. 3.

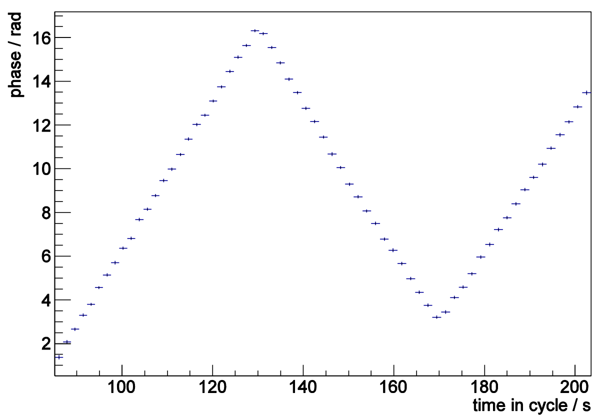

FIG. 3. (Preliminary) Measurements of the phase (rad) in successive time bins during a store in which the rf cavity frequency is changed to a new value at 120 s and returned to the original value at 170 s.

The inflection points where the spin tune was changed are obvious, and the slope in between is clearly determined. A series of such tests using different revolution frequency changes allowed a measurement of the coefficient $G\gamma\beta^2/\eta f$ for several values of the spin tune change. Using the nominal values above for this quantity yields 7.396×10^{-8}. This compares well with the measured value from the slopes of the time bin phase of $7.682(3) \times 10^{-8}$ (see Fig. 4), even though these data come from different COSY machine setups.

This demonstrates that the first type of change, the alteration of the spin tune, works as expected.

A second test was made by programming a series of jumps, each designed to modify the phase by one radian. This result is shown in Fig. 5 (after selecting the spin tune that gives the most stable phase history).

These two successful tests show that it is possible to use small changes to the rf cavity frequency to make controlled changes to either the spin tune or the phase of the rotating IPP in the COSY storage ring.

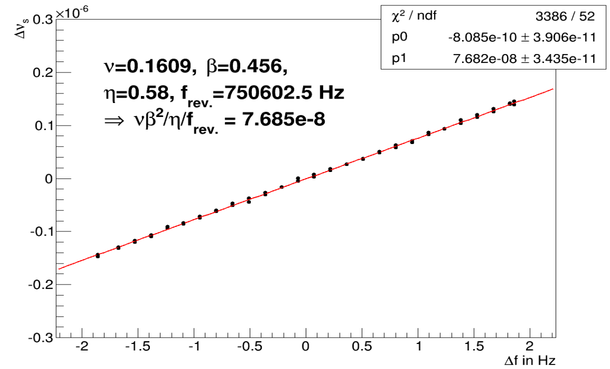

FIG. 4. (Preliminary) Measurements of the change in spin tune as indicated by the change in slope in Fig. 3 as a function of the size of the frequency jump. The red line is a linear fit through these data, which generated the value of η shown in the plot. This value agrees well with typical COSY machine parameters [5] (see text).

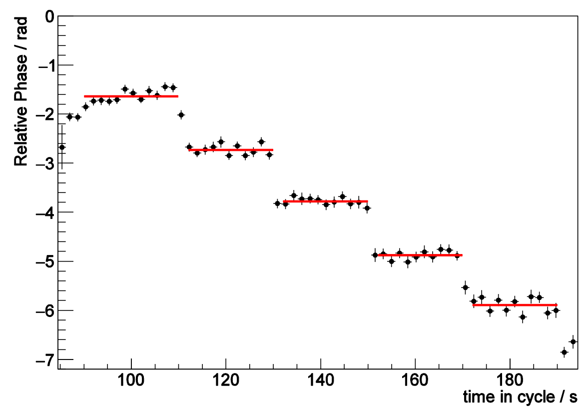

FIG. 5. (Preliminary) Measurements of the phase for a single store in which the rf cavity frequency was changed briefly, then restored. Each frequency pulse was designed to allow for a precession of the IPP phase by one radian. The initial spin tune reference value was adjusted to create a flat phase history. The red lines mark steps of one radian.

IV. POLARIZATION RECAPTURE, A MODEL OF THE PRECURSOR EXPERIMENT

Any precession of the IPP about the radial direction due to the interaction of an EDM with the radial electric field is canceled in the COSY ring because of the precession of the IPP about the vertical magnetic field axis in the ring dipole magnets. A small step made when the IPP is parallel to the velocity is countered by an opposite step when the IPP is anti-parallel to the velocity. This cancellation may be broken by an rf Wien filter whose magnetic axis is vertical. The net effect of the filter is on the precession of the magnetic anomaly about the vertical axis; there is no effect due to the EDM, which is affected only by the Lorentz force that vanishes inside the Wien filter. The filter may be operated so that it slows down the magnetic precession when the IPP is forward and speeds it up when the IPP is backward. Thus the cancellation is no longer complete, and an EDM precession will accumulate over time.

This "precursor" experiment (made instead of the frozen spin experiment) requires a feedback control of the rf Wien filter frequency to match its oscillations to the rotation of the IPP. A similar demonstration experiment could make use of an rf solenoid to rotate the IPP into the vertical direction, the opposite of the procedure used to rotate the polarization from the vertical into the horizontal plane at the beginning of the store. But this will not work unless the IPP is sideways when the rf solenoid strength goes through its peak (*i.e.*, it has the correct phase). So a feedback system was created to send corrective pulses to the rf cavity frequency generator based on the measured phase of the IPP during a single (or short group of) time bin(s). In this way we could maintain the IPP phase relative to the rf solenoid oscillation.

The sequence of events in this experiment is shown in Fig. 6.

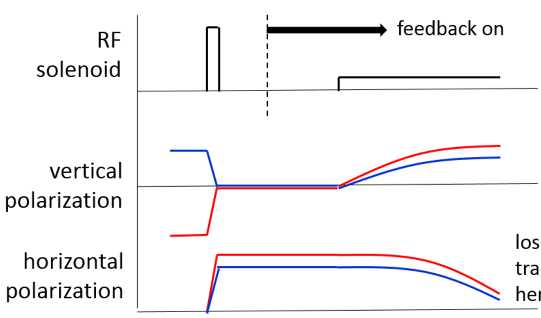

FIG. 6. History of the polarization recapture experiment. The blue and red traces indicate the values of the vertical or horizontal polarization for the two (positive and negative) polarization states. See the text for details. Feedback tracking is lost when the IPP vanishes.

As a function of the time during the store, the rf solenoid begins the process by being operated for a time long enough to allow the initial vertical polarization to be rotated into the horizontal plane. The vertical polarization component of the spin up (blue) and down (red) states goes to zero. (These two states are shown with unequal polarizations.) At the same time the IPP magnitude rises. At a later time, the feedback loop is started and a particular target value of the phase is chosen. Later still the rf solenoid, its frequency generator now locked to the rotating polarization, is turned on at a low power level. By this time, the IPPs of the two polarization states (which are recorded on different beam stores) have been rotated by the feedback system to be in the same direction. Then the IPPs will rotate into the vertical direction at a rate determined by the relative phase of the IPP rotation and the rf solenoid (see Figs. 7 and 8).

An example of this process is shown in Fig. 7.

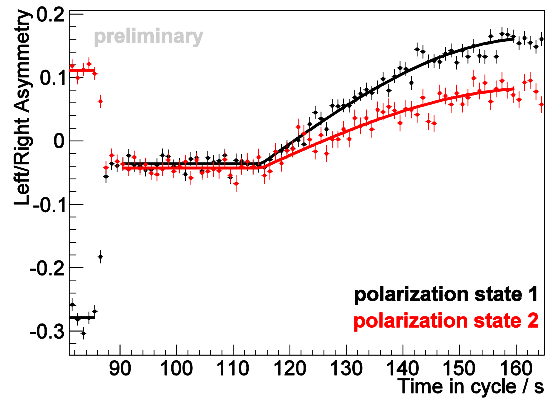

FIG. 7. Measure of the spin up (red) and spin down (black) asymmetries as a function of time, following the pattern of Fig. 7 for the vertical polarization.

Before 86 s, each polarized state appears with its own value. At 86 s the rf solenoid rotates the polarizations into the horizontal plane. And at 115 s the rf solenoid goes on again. The polarization increases. Fig. 8 shows that the amplitude of the initial slope depends on a sine function of the phase for both polarization states, as expected.

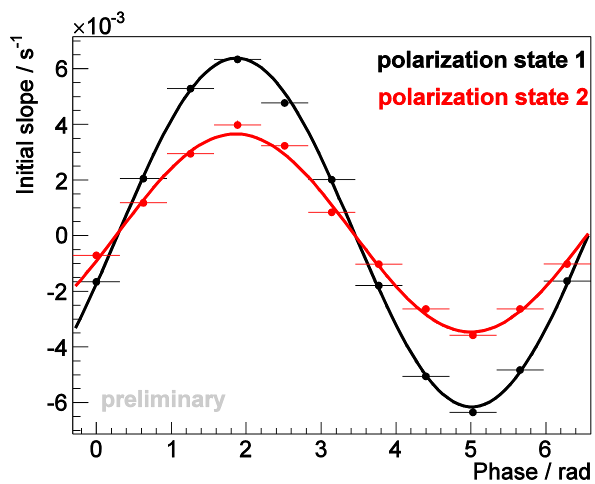

FIG. 8. The amplitude of the initial slope during the second period of rf solenoid operation is shown for both polarization states as a function of the phase. The curves are fits that adjust only the magnitude and phase of the sinusoidal function. The different initial polarizations result in different amplitudes.

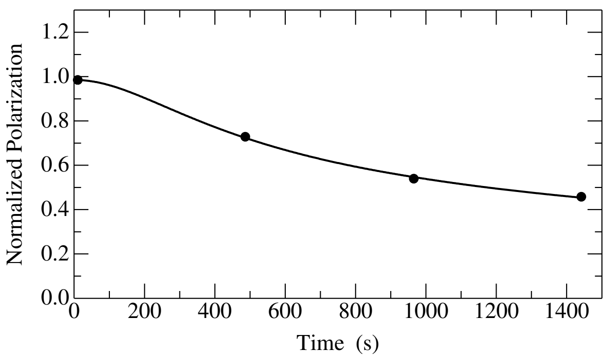

FIG. 9. Measurements of the IPP (normalized) made at four sampling points during a long store. The curve is the shape expected for a Gaussian distribution of betatron amplitudes whose width is adjusted to match this IPP lifetime. The half-life of the polarization is 1173 ± 172 s.

V. LONG IN-PLANE POLARIZATION LIFETIME

These observations require that the IPP lifetime be long enough to allow a series of tests of the feedback system. The procedure for establishing a long lifetime is the result of tests made since 2012. The main mechanism for the loss of IPP in a coasting beam is the momentum spread, which yields lifetimes in the range of tens of milliseconds. Simply bunching the beam can increase the lifetime by about two orders of magnitude. In the COSY ring, polarization decoherence in the bunched beam appears to arise mostly from path-lengthening due to betatron oscillations, either vertical or horizontal. If the phase space for the beam is reduced through the application of electron cooling, the lifetime again increases. To do a better job, the optics of the machine lattice must be adjusted so that the path length increase is canceled by sextupole fields operating in regions of either a large beta function or a large dispersion.

The COSY lattice contains three families of sextupole magnets located in the arcs. We developed procedures for scanning the sextupoles to locate the settings of greatest IPP lifetime [4]. These places are also associated with zero values of the chromaticity. A series of scans taken at the end of 2015 with beams of less than 10^9 deuterons/fill showed good properties and the longest lifetimes. One of these scans, as seen in Fig. 9, shows the results for a beam where the electron-cooling runs for 75 s and then is turned off.

VI. CONCLUSIONS

This contribution has reported on the recent advances in the observation of deuteron IPP in the COSY storage ring. Using a combination of bunching, electron cooling, and sextupole field adjustment, the IPP lifetime can be extended to over 1000 s. In addition, feedback from the polarimeter may be used to regulate the spin tune of this beam, including the phase. A test measurement shows that the capability exists to recapture this polarization using an rf solenoid with a vertical precession rate dependent on the relative phase between the beam and the solenoid. This illustrates that the ingredients are present to have an out-of-plane precession sensitive to the EDM.

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