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Search for an electric dipole moment with polarized beams in storage rings

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The search for an electric dipole moment (EDM) using a polarized, charged-particle beam in a storage ring requires ring conditions that can maintain a longitudinal polarization for times up to 1000 s. This situation is unstable against the spread of the particle spins in the horizontal plane, so a method to control this effect must be demonstrated. For this reason, a series of dedicated studies is being performed at the COoler SYnchrotron (COSY) at the Forschungszentrum-Jülich to examine the effects of emittance spread on the spin coherence time. To support these studies, a novel polarimeter system has been developed that can monitor the horizontal polarization of the beam circulating in the ring as it precesses at ~120 kHz

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1. Introduction

An electric dipole aligned along the spin axis of a fundamental particle, nucleus, or atomic system violates both parity conservation and time reversal invariance. The observation of such a phenomenon would, at the present or proposed levels of sensitivity, signal new physics beyond the Standard Model.

The usual method for identifying an electric dipole moment (EDM) in such searches is to observe the rotation of the spin axis or polarization under the influence of a strong electric field. The use of a storage ring opens the search to charged, polarized particles that would otherwise not be manageable in such a field.

The best procedure begins with the alignment of the beam polarization along the velocity of the beam followed by the observation of any slow rotation of that polarization into the vertical direction due to a strong radial electric field. This imposes several feasibility requirements. First, the ring must utilize a special combination of electric (and possibly magnetic) fields in order to ensure that the usually unstable polarization along the direction of the velocity remains for times up to 1000 s to allow any EDM effect to accumulate to a measurable level. Second, the beam must be slowly sampled during the storage time by a polarimeter capable of detecting a change in the vertical polarization of several μrad over the 1000 s storage time.

The required large polarimeter efficiency and polarization sensitivity may be achieved by continuously extracting the beam onto a carbon target several cm thick. In combination with an array of calorimeter detectors that emphasize elastic scattering events at forward angles, it has been shown to be possible to meet these requirements for an EDM search [1]. This demonstration was made using 0.97-GeV polarized deuteron beam and the EDDA detector [2,3] located on the Cooler Synchrotron (COSY) at the Forschungszentrum-Jülich [4]. First results covering the contribution of synchrotron oscillations to RF-solenoid induced spin resonances may be found in Ref. [5].

One of the problems connected with the requirement of maintaining a large horizontal polarization for the 20 min needed for the EDM effect to accumulate, arises from spin-decoherence effects. Normally, momentum spread among the beam particles leads to differences in the precession rates and the particle spins will decohere by spreading in the horizontal plane. The linear part of this effect may be canceled by using an RF cavity to bunch the beam, thereby imposing the same average cyclotron frequency on each particle. However, a lengthening of the orbital path that depends quadratically on the size of horizontal and vertical betatron oscillations while maintaining the cyclotron frequency will generate a smaller spread in spin precession rates that will lead to decoherence over a longer time. At this smaller level, there may also be a contribution that depends on the square of the deviation of the momentum from the central value. One of the goals of the EDM ring development program is to understand how to reduce or correct for such quadratic or higher order effects by, for example, adjusting the ring sextupole field components or cooling the beam. In this paper we present the first results from a series of dedicated studies performed at COSY to examine the use of higher-order (sextupole) fields in the storage ring to lengthen the coherence time of the stored, horizontal beam polarization. To support these studies, a novel polarimeter system has been developed that is capable of monitoring the horizontal polarization of the beam circulating in the ring as it precesses at ~120 kHz.

2. Measurement of the horizontal polarization.

One concept for the EDM polarimeter involves stopping detectors that deliver their largest signals for elastic scattering events. Reactions that produce lower energy particles, usually a deuteron or a proton, are removed with an absorbing medium between the target and the detector. A similar arrangement was achieved using the scintillators of the EDDA detector. Long scintillators, called “bars", ran parallel to the beam and were read out with photomultiplier tubes mounted on the downstream end. These 32 scintillators were divided into groups of 8, corresponding to scattering into the left, right, down, or up directions. Outside the bars were “rings" that intercepted particles scattering through a range of polar angles beginning at 9.1^o. The signals coming from the bars can be properly combined into left/right and up/down asymmetries sensitive to beam vertical and horizontal polarization respectively. The scattering target for the polarimeter was a carbon tube 17 mm long that surrounded the beam. Slow extraction of the beam onto the target was achieved by locally steering the beam vertically upward into the top edge of the tube. The EDDA polarimeter setup is schematically shown in Fig. 1.

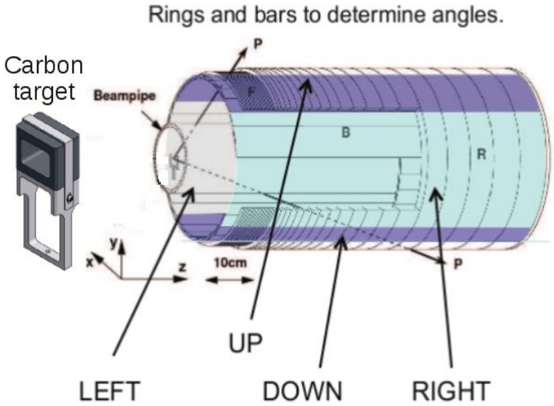

Figure 1. Schematic view of the EDDA polarimeter.

The goal of the experiment presented here is to investigate the decoherence caused by the spread of the particle spins on a horizontally polarized beam. In order to obtain a value for the horizontal polarization from asymmetry measurements, a way has to be provided to determine the direction of the polarization at the instant that each event takes place in the EDDA detectors.

For this purpose, a special TDC was created by the Electronics Group (ZEA-2) in the Forschungszentrum. It contains a clock with a programmable time step that we have used with steps between 80 and 96 ps. Each event is marked with the clock reading and these values are passed directly to the data file. For reference, a prescaled version of the COSY rf-cavity oscillation is used to calibrate this clock against the machine rf. From these data streams, it is possible to assign a turn number to each event after the timing start signal for each store is generated. The fractional part of the turn number indicates where the detected deuteron was relative to other deuterons in the bunched beam. To illustrate this, Fig. 2 shows a distribution of events during the time of one store. The vertical axis represents the full range of the 183-m ring circumference. After loading the beam and acceleration, cooling starts. Bunching is turned on at 11 s, and the beam collects into a well-localized bunch until cooling is turned off at 30 s. There is a short period of 10 s that was reserved for selective heating of the beam. At 41 s, the beam at the EDDA target is moved to begin extraction onto the target, creating a flash in the detectors.

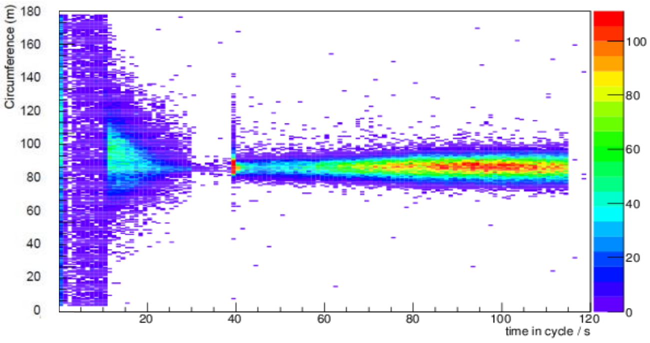

Figure 2. Graph of events recorded in the EDDA scintillation detectors (used as a polarimeter) as a function of time (seconds) in the store horizontally and location on the ring circumference (arb. units) vertically. See text for details on the processes depicted here.

Since the EDDA detector occupies one spot on the ring, an increment of one turn in the bunched beam represents a fixed angle of polarization precession. So the integer part of the turn number is multiplied by the spin tune ($G\gamma$, where G is the anomalous magnetic moment and γ is the relativistic parameter), yielding the total spin precession angle (θ) since the start time. When expressed in rotations ($\theta/2\pi$), the fractional part of the total angle indicates the direction on the horizontal plane for the polarization. When the spin tune is correctly chosen, the events may be divided into directional bins and the down-up detector count rate asymmetry will show a sinusoidal oscillation around the circle of all directions in the horizontal plane. A fit, as shown in Fig. 3 to the asymmetry yields the best oscillation and a value of the magnitude of the polarization.

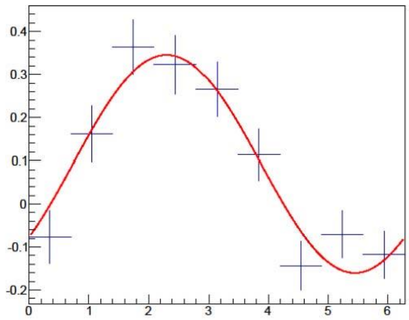

Figure 3. Measurements of the sideways polarization as a function of the direction (0 to 2π) in the horizontal plane. The directions are divided into nine bins. Events are sorted into the bins on the basis of the fractional part of the total polarization rotation angle. In each bin, the down-up asymmetry is calculated. The red curve represents the best sinusoidal fit to the measurements with adjustable magnitude, phase, and vertical offset. The magnitude is retained as a measure of the horizontal polarization within the time bin that provided the events used to calculate the asymmetries.

3. Effect of betatron oscillations on tune spread and sextupole corrections.

In May 2012 the first set of data from the time marking system has been produced. This data was taken with a wide "ribbon" beam that was deliberately kept short vertically to suppress contributions to the spin decoherence from emittance in that direction. The population size of all dimensions in phase space was first reduced by cooling. Then the effective horizontal spread was increased by the application of a white noise electric field applied to a pair of horizontally separated plates. With this beam, short spin coherence times (SCT) were observed (Fig. 4). Using a definition of the SCT as the time required for the polarization to fall to 0.606 (Gaussian half width) of its initial value, the SCT in Fig. 4 is about 5 s.

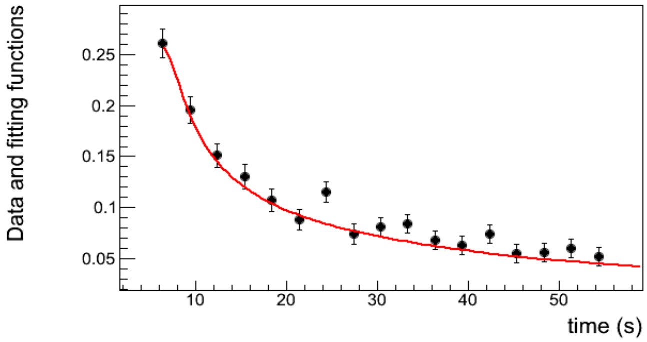

Figure 4. Measurements of the magnitude of the horizontal polarization as a function of time.

In a successive stage, adjustments to the sextupole field in the ring were made by adding current to the MXS family of four magnets located at the beginning and end of each of the two COSY arcs. The spin coherence times are shown in Fig. 5. The sextupole field size is given by the K2 coefficient. The measurements show a clear peak near 200 s for a field of 5.5 1/m^3. (This time is significantly longer than the 10 s reported [6] for maintaining the horizontal polarization of electron and positron beams.).

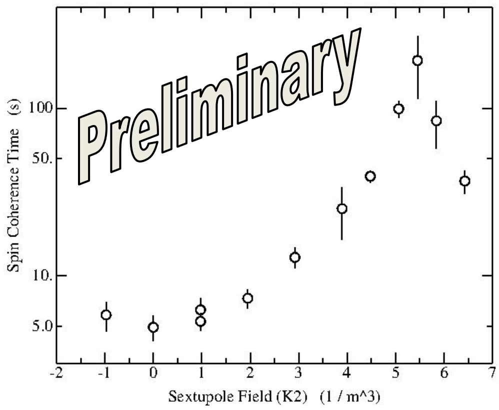

Figure 5. Spin coherence time, measured as the horizontal polarization lifetime (Gaussian width) as a function of the correcting sextupole field available from the MXS sextupole magnet set.

A more precise analysis may be made using the reciprocal of the spin coherence time. In this case we expect based on lattice beam transport models that the variation will be linear in the sextupole fields:

$$\frac{1}{\tau_{SCT}} = [A - a_1 S - a_2 L] X^2_{RMS} + [B - b_1 S - b_2 L] Y^2_{RMS}$$

where the uncorrected spin tune spread is represented by the horizontal and vertical values of A and B. The magnet currents in two different sextupole magnet sets of the COSY machine, are given by S and L. Their influence is mediated by the a_i and b_i coefficients that represent the contribution of the horizontal and vertical beta functions at the location of the sextupole magnets. In the test just described, only the value of the S set is large, and only the a_1 term is actively varied since Y_{RMS} is small as a result of initial electron cooling. The S and L families emphasize respectively the X and Y components of the beam. Thus this test is only for the major contribution to the horizontal correction

The results for plotting the reciprocal of the spin coherence time as a function of sextupole current are shown in Fig. 6. The points above the crossover value of the magnet strength have been plotted with their signs reversed to demonstrate the linearity of the effect. The black curve was made with a large heating power, thus leading to the widest beam in the experiment. The red and the blue curves were made with about a factor of two less power, but at different times during the run. In between those times, changes to the ring setup for focusing led to different slopes for the sextupole current curves. The lines all show a common zero crossing point, thus agreeing on the field needed to cancel the horizontal spin tune spread.

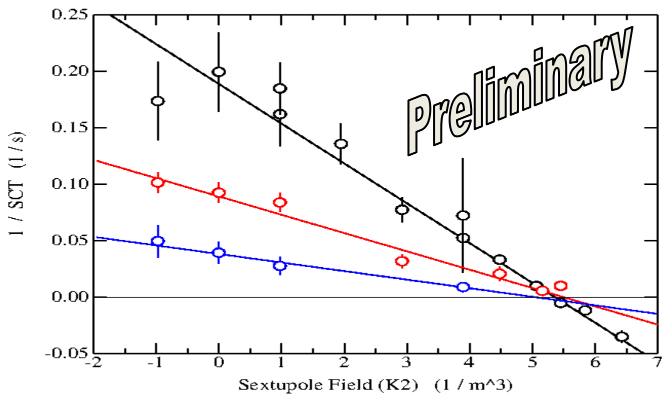

Figure 6. Spin coherence time, measured as the horizontal polarization lifetime (Gaussian width) as a function of the correcting sextupole field available from the S sextupole magnet set.

4. Conclusions and outlook.

A novel polarimeter based on a time stamp system has been developed to monitor the precession of the horizontal polarization of a stored deuteron beam in the COSY ring. With this tool in hand, a series of dedicated studies have been performed to examine the effects of emittance spread on the spin coherence time. The compensation of the horizontal emittance by means of sextupole field has been effectively demonstrated and spin-coherence times significantly longer than previously reported have been reached.

As a natural extension of the work presented here we are presently investigating the perspectives for using different sets of sextupoles to compensate both the emittance spread and the quadratic momentum dispersion at the same time.

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