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Spin coherence time measurements for a polarized deuteron beam

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Summary. — The measurement of a non-zero electric dipole moment (EDM) of a fundamental particle would probe new physics beyond the standard model. It has been proposed to search for the EDM of charged particles using a storage ring. The polarization of the charged particle beam is initially aligned along the velocity and the EDM signal would be a rotation of this polarization into the vertical direction as a consequence of the radial electric field always present in the particle frame. This experiment requires ring conditions that can ensure a longitudinal, and stable, polarization (spin coherence time, SCT) up to 1000 s. A study is beginning at the COoler SYnchrotron (COSY) located at the Forschungszentrum-Jülich to examine the effects of emittance and momentum spread on the SCT of a polarized deuteron beam at 0.97 GeV/c. A special DAQ has been developed in order to provide the first direct measurement of a rapidly rotating horizontal polarization as a function of time. The preliminary tests presented here will show how the horizontal emittance affects the spin coherence time and how the SCT can be increased using sextupole magnets. The longest horizontal polarization lifetime recorded is $\tau(1/e) = 316 \pm 40$ s.

PACS 29.20.db – Storage rings and colliders.
PACS 29.27.Bd – Beam dynamics; collective effects and instabilities.
PACS 29.27.Hj – Polarized beams in particle accelerators.
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1. – Introduction

The Electric Dipole Moment (EDM) of a fundamental particle is a permanent charge separation within the particle volume, aligned along the spin axis. The EDM violates both parity conservation P and time reversal invariance T. Assuming the validity of the CPT theorem, T violation corresponds to CP violation so that the EDM could point to one of the missing sources necessary to understand the universe's evolution from an initial matter-antimatter symmetric configuration to a universe dominated by matter. The standard model predicts a non-vanishing EDM (*e.g.*, for proton $|d_p|_{SM} < 10^{-32}$ e·cm) but it is too small for both the explanation of the baryon asymmetry and experimental observation at present levels of sensitivity. Models beyond the standard model predict values within the sensitivity reach of current or planned experiments (for proton and deuteron $|d_{p,d}| \rightarrow 10^{-29}$ e·cm), so EDM searches represent a sensistive probe for new physics. At the moment, no EDM has been observed on a fundamental particle.

Detection methods rest mainly on observing the precession of the polarization in an external electric field. This restricts searches to neutral systems, such as neutral particles, atoms, molecules, and bulk matter. Beginning with a longitudinally polarized beam in a storage ring, the EDM can be detected as a rotation of the polarization of a charged particle from the longitudinal to the vertical direction, due to the interaction with the inward radial electric field that is always present in the particle frame.

In a normal storage ring, the polarization will precess about the vertical direction, giving an anomalous rotation relative to the velocity of

$$\vec{\omega_a} = \vec{\omega}_s - \vec{\omega}_c = -\frac{q}{m}\left\{G\vec{B} - \left[G - \left(\frac{m}{p}\right)^2\right]\frac{\vec{\beta}\times\vec{E}}{c}\right\}, \tag{1}$$

where ω_s is the spin precession in the horizontal plane, ω_c the particle angular frequency and $G = \frac{g-2}{2}$ the anomalous moment (called a for leptons). In order to keep the spin aligned along the velocity, the frozen spin technique requires that ω_a vanish. Since the proton $G = 1.79$ and deuteron $G = -0.14$ have anomalous moments of the opposite sign, this requirement must be satisfied in two different ways. In the proton case at $p = 0.7\,\mathrm{GeV}/c$ ("magic momentum") the expression in square brackets is zero. In a pure electric ring the magnetic field is absent and ω_a is also zero. A magic momentum for deuterons does not exist. Using both magnetic and outward electric fields, the frozen spin condition is fulfilled.

In a magnetic storage ring, the stable spin direction is along the vertical axis, orthogonal to ring plane. Hence any horizontal spin component will start precessing about it with a frequency proportional to the *spin tune*

$$\nu_s = G\gamma, \tag{2}$$

which defines the number of spin precessions per turn and γ is the relativistic factor. Starting with a longitudinally polarized beam, after a while all the particle spins will spread out in the horizontal plane because of the different particle velocities and the horizontal polarization will vanish. Thus, the time available to observe the EDM signal is given by the horizontal polarization lifetime, or the *spin coherence time*.

In order to achieve a sensitivity of 10^{-29} e·cm, a good compromise for the experiment requires a polarimeter sensitivity of 10^{-6} rad and a storage time of 1000 s, during which the horizontal polarization has to be maintained.

2. – Experimental setup

The COoler SYnchrotron COSY [1] at the Forschungszentrum-Jülich, represents the ideal place for the feasibility studies of the deuteron EDM experiment. It is a ring of 184 m length where beams of polarized and unpolarized protons and deuterons are available in a momentum range from 300 MeV/c to 3.7 GeV/c.

There are several instruments available for beam and polarization manipulation:

– the electron cooler to shrink the transverse beam size (emittance) and the particle momentum spread,

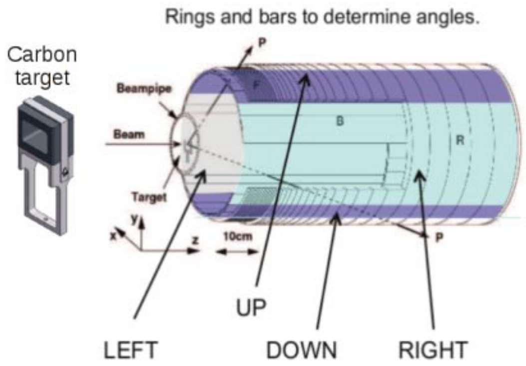


Fig. 1. – The carbon target used to extract the beam is placed in front of the EDDA detector. The left and right sectors are highlighted in light blue while up and down sectors are in blue.

- an RF-solenoid to move the polarization from the vertical (stable) axis to the horizontal (ring) plane by inducing a spin resonance,
- the EDDA [2] detector (see fig. 1) used as a mock EDM polarimeter to measure the vertical and the horizontal polarization components as a fuction of time.

A vertically polarized deuteron beam was injected into COSY, accelerated to a momentum of $p = 0.97\,\text{GeV}/c$, bunched at the first harmonic, and then continuously extracted onto a thick carbon target (15 mm long, see fig. 1). The polarization was measured with the EDDA polarimeter composed in part of 32 scintillators called "bars" divided into groups of 8, corresponding to scattering to the left, right, down, or up directions. Outside the bars were "rings" that intercepted particles scattering through a range of polar angles from 9.1° to 20.1°, where the spin sensitivity of deuteron elastic scattering on carbon is high [3]. From the counting rates into the four directions it is possible to calculate the asymmetry ϵ which is proportional to the beam polarization. In particular,

$$\epsilon_{DU} = \frac{D-U}{D+U} \propto p_h, \tag{3}$$

where D and U are respectively the counting rates from the down and up sectors and p_h is the horizontal polarization. For the measurement shown here, it is not necessary to know the exact value of the polarization but it is enough to know how the asymmetry value changes with time in order to study the influence of beam emittance on the spin coherence time.

In order to rotate the polarization into the ring plane (null vertical polarization), the RF-solenoid was operated at the spin resonance:

$$f_{res} = f_{cyc}(1 - G\gamma), \tag{4}$$

where $f_{cyc} = 750602.5\,\text{Hz}$ is the cyclotron frequency and $G\gamma$ is the spin tune defined in eq. (2).

3. – Spin coherence time measurement

3˙1. *Data acquisition system.* – The most critical new capability needed to measure the spin coherence time was the development of a "time-stamp system" which made possible recording the horizontal polarization as a function of time while it precessed at 120 kHz. Thanks to the efforts of E. J. Stephenson, who prepared the project, and V. Hejny, who wrote the DAQ software, the first direct measurement ever of the rapidly rotating horizontal polarization was accomplished.

The TDC, a ZEL GPX Time-to-Digital Converter (created locally at the Forschungszentrum-Jülich) marked the polarimeter events with the elapsed time from a continuously running clock. The clock period of the TDC was 92.59 ps, a value much smaller than the COSY beam revolution time of 1.332 μs. This allowed good resolution on the longitudinal position of a detected particle within the beam bunch. Once the rf cavity signal and the TDC oscillator were cross-calibrated so that the turn number since DAQ start could be calculated, it became possible to use the fractional part of the turn number to provide a map of the particle distribution within the beam bunch.

The next step was the calculation of the total spin precession angle which required the integer part of the turn number and the knowledge of the spin tune frequency, $G\gamma f_{cyc}$ (about 120 kHz) which may be obtained from the difference between the rf solenoid resonance frequency and the cyclotron frequency (see eq. (4)). The rf solenoid spin resonance was determined at the beginning of the experiment using a variable-frequency Froissart-Stora [4] scan across the resonance (which flips the vertical polarization component) and refined with a series of fixed-frequency scans to locate the center of the resonance to within an error of about 0.2 Hz. With this as a start, the total horizontal polarization precession angle was calculated for each event as the product of the spin tune and the integral part of the turn number:

$$\omega_{TOT} = 2\pi\, G\gamma\, \mathrm{Int}(N_{turns}). \tag{5}$$

The circle around which the polarization precessed was divided into 9 bins and polarimeter events from the up and down detector quadrants sorted separately into each bin. The experimental challenge was the high frequency of the polarization precession. One full precession corresponded to only 6 turns of the COSY beam (about 8.3 μs) while the rate of the elastic scattered deuterons was approximately one in 700 turns. Thus, the accumulation time of 3 s was chosen and the down-up asymmetries were calculated for each bin and reproduced with a sine wave of variable magnitude, phase, and offset (which is non-zero if there is a systematic difference in the detector acceptances). The magnitudes from successive 3-second accumulation times were strung together to create a history of the horizontal polarization during the store. Figure 2 shows horizontal polarization asymmetries measured for small to large horizontal beam profiles. As the profile becomes larger, the spin coherence time shrinks because of the larger spread in spin tunes. The measured data (open circles) are subject to a positive bias since fitting a sine wave with an undetermined phase to a random distribution always produces a non-zero magnitude. An initial correction for this effect produces the solid data points but a better method that also determines the spin ocherence time [5] is described in the next section.

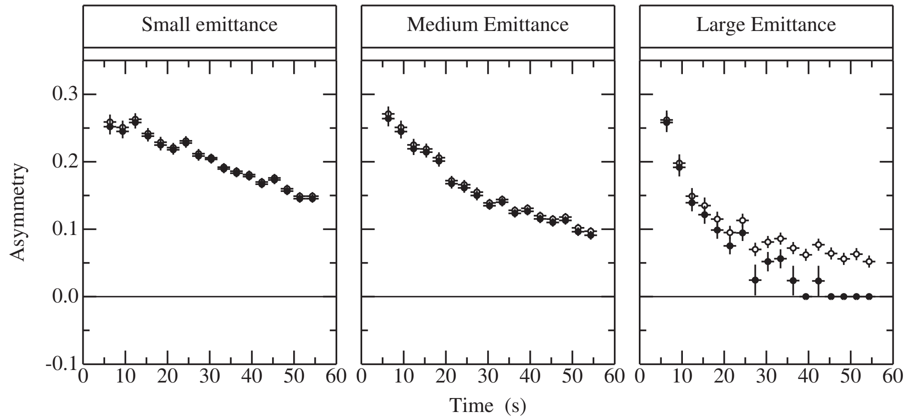
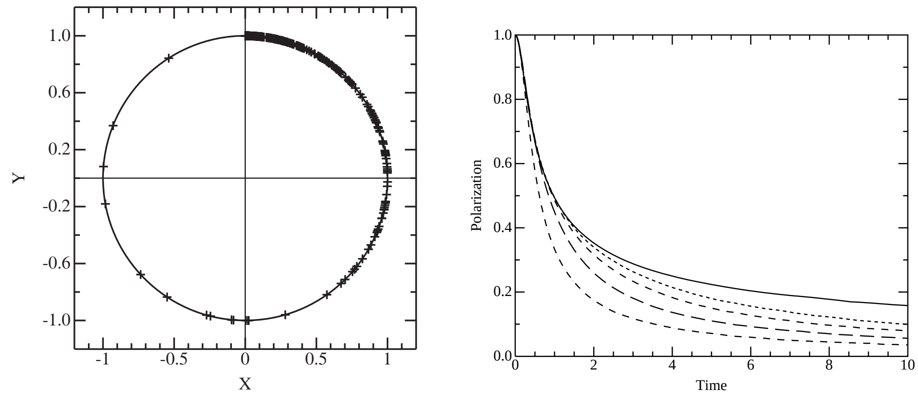


Fig. 2. – The three panels show the horizontal polarization asymmetries measured for small, medium and large horizontal beam profiles, respectively. As the profile becomes larger, the spin coherence time shrinks. A positive offset of the measured data (open circles) at low asymmetry comes from the fitting process using of a sine wave with an undetermined phase to reproduce a random distribution. An initial correction for this effect produced the solid data points.

3˙2. *Extracting spin coherence time with correction of the systematic positive bias.* – The time-dependent shapes shown in fig. 2 are neither Gaussian nor exponential, so a numerical template was matched to the data in order to characterize the shape with a value of the spin coherence time. This also allowed the correction for the systematic positive bias to be applied to the template, a procedure that is much better defined than correcting the asymmetry measurements directly.

The template assumes that the spread of spin tunes is due solely to the path lengthening associated with the finite X and Y emittances of a bunched beam. At any point in the ring with known beta functions, the emittance may be characterized by the angles θ_X and θ_Y that represent the maximum deviation from the direction of the central orbit. The change in spin tune depends on the combination $\theta_X^2 + \theta_Y^2$ for each particle track. The values for θ_X and θ_Y were chosen from two separate Gaussian distributions, each characterized by a width, σ_X and σ_Y. Changing these widths relative to one another alters the time-dependent shape of the template curve, which may then be characterized by $\alpha = \sigma_Y/\sigma_X$. A change to the spin coherence time itself is equivalent to rescaling the time axis t of the template curve, $F_\alpha(t)$. During the experiment, it was possible to make σ_X, originally reduced through electron cooling, wider by applying white noise to a set of horizontal-field electric plates. Thus all tests were made with horizontal ribbon beams whose cross-sectional shaped represented cases with $\alpha < 1$.

The template shapes were constructed by taking 10^6 spins and distributing them around a unit circle (in the storage ring plane) in accordance with the spin tune model just described for a particular value of α. An example of such a distribution for 300 spins and a single non-zero emittance is shown in fig. 3(a). At $t = 0$ all of the spins were at $(X, Y) = (0, 1)$ and the beam represented by this ensemble was completely polarized ($p = 1$). As time increases, the points revolve around the unit circle in one direction (increasing spin tune) since the quadratic sum of the angles is always positive. The distribution was allowed to spread linearly with time. At each time point, the X and Y components of the polarization were calculated, and the total polarization determined



(a) (b)

Fig. 3. – Panel (a) shows the unitary circle in the XY-plane where the spin are distributed following the square of a Gaussian distribution. It represents the spin positions in the plane at one time. Panel (b) shows five example of the numerical function used to describe the horizontal polarization as a function of time. These curves have the same properties except for the α value which is equal to 1, 1/2, 1/3, 1/4 and 0 (starting from the bottom). $\alpha = 0$ means that the beam is horizontal and flat because the vertical size is zero. $\alpha = 1$ is a round beam, the case in which the beam emittance effect on polarization is the largest.

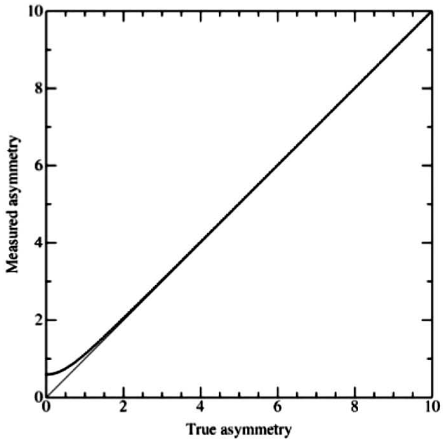
by adding these components in quadrature. For the single distribution case ($\alpha = 0$), the resulting polarization time dependence is the solid curve in fig. 3(b), or $F_0(t)$. For larger values of α with σ_X fixed, the template curve falls more quickly, as shown by the broken curves in fig. 3(b).

The initial departure of the template shape from one at small times is quadratic and in this respect like a Gaussian function. We chose as the "spin coherence time" the width at $p = 0.606$, the same value that corresponds to the amplitude of a Gaussian function whose argument is the functions width σ. In order for this to work for the double distributions represented here, it is necessary to scale the template curve according to $F_\alpha(\sqrt{1+\alpha^2}\,t)$. The curves in fig. 3(b) include this scaling and remain well-matched to each other down to $p = 0.6$. Other parameters were included in order to match individual sets of asymmetry measurements and produce the adjustable template:

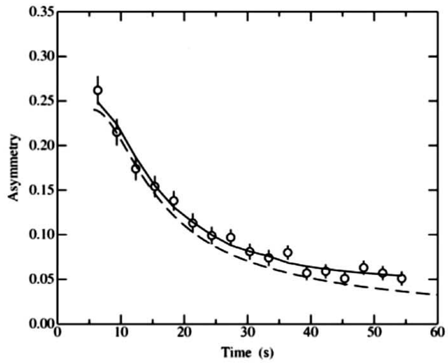
$$f(\alpha, t) = a_1 F_\alpha(a_2\sqrt{1+\alpha^2}\,t + a_3), \tag{6}$$

where a_1 scales to match the asymmetry at the start of the horizontal polarization measurement, a_2 is proportional to the spin coherence time, and a_3 is a time shift used to synchronize the template with the start time in the data stream. The numerical lookup table is based on a fixed array t whose interpretation as experimental time is given by $a_2\sqrt{1+\alpha^2}\,t + a_3$. The matching of the template to each data set was done with a numerically driven non-linear regression routine.

The amount of positive bias in the extraction of the amplitude of a sine wave representation of the 9 asymmetry points around the horizontal plane depends on the size of the statistical errors in the 9 points. These errors are typically similar for all bins, and a single average value is used. The value of the positive bias is the average magnitude of the sine wave fit to data with a random and a signal component. The larger the error,



(a)



(b)

Fig. 4. – Panel (a) shows a Monte Carlo simuation relating the observed asymmetry with the real asymmetry. The positivity problem becomes evident when the real asymmetry goes to zero and the error is about the size of the typical signal. Panel (b) is an example of the positivity correction. The empty circles are the uncorrected data interpolated with the numerical function (solid line). The real polarization which correspond to the data after the correction is represented by the dashed line.

the larger is the positive bias. This effect is shown in fig. 4(a) where each axis is plotted in units of the typical error in a single angle bin. Below one, this bias becomes large. It is approximately, but not exactly hyperbolic, so the numerical table represented by fig. 4(a) was used to calculate the correction in each case. The asymmetries shown in fig. 2 represent an average over typically 15–20 storage cycles at COSY. While the error on the average becomes smaller, the bias remains the same. For each template shape and data point, the bias was calculated knowing the individual angle bin error and applied to the template curve. An example is shown in fig. 4(b) by the solid curve in comparison to the original template shape as a dashed line.

A set of template curves were generated for a range of α values between 0 and 1. Nonlinear regression fits were made for each template, and the final value of the spin coherence time taken from the one with the smallest reduced chi square. In general, this correlated well with changes in the ribbon beam shape during the experiment. Additional error contributions from the fitting process were added to the statistical errors when quoting the final spin coherence time.

4. – Emittance effects

There are two kinds of contributions to the spin tune spread from beam dynamics. At first-order, the spin tunes spread because of the spread of particle momenta described by the momentum distribution of $\Delta p/p$, where p is the reference value. This is removed by bunching the beam. A second-order contribution appears due to betatron oscillations that occur when beam particles oscillate about the central trajectory. Since bunching the beam keeps all particles on average isochronous, such oscillations lead to a longer beam path, a higher particle speed, and a change in the spin tune. The change in path length

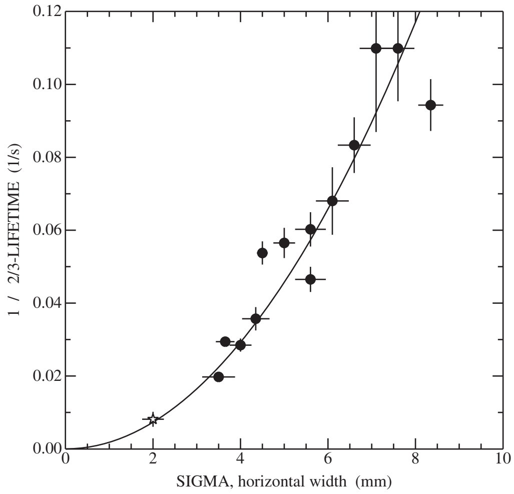


Fig. 5. – Measurements of the reciprocal of the horizontal polarization lifetime, here chosen to be the time required for the beam to lose 1/3 of its initial polarization. The horizontal axis is the average beam profile Gaussian width in mm. Both quantities represent values from a preliminary analysis during the experiment. Only the point with the star was measured with electron cooling running during data taking. The solid line represents a guide to the eye with a parabolic function.

goes as the square of either the maximum angle of deviation from the central ray or the maximum displacement. Then, it is expected that the reciprocal of the polarization lifetime should go as the square of the width of the beam profile, as appears to be the case in fig. 5.

The goal was to study separately the size of the effects in both X (radial) and Y (vertical) directions. But it proved difficult during the run to find a machine condition where the vertical emittance could be varied by itself (through electron cooling and then selective heating with white noise on electric field plates) while keeping the beam bunched. However, this was possible in the horizontal direction. So that degree of freedom was explored. Extraction of the beam was made through a vertical steering bump that brought the beam close to the thick polarimeter target. This helped to keep the size of the vertical emittance small so that changes could be related to the horizontal profile.

Figure 5 shows a set of measurements for several profile widths (solid points). All of these were taken with electron cooling off, following a period with cooling on to reduce the phase space size with another short period of heating to expand the space horizontally. This gave profile sizes typically larger than 4 mm. A single point at 2 mm (star) was taken with cooling running continuously through the measurement.

5. – Sextupole corrections

Sextupole magnetic fields, which vary as the square of the radius from the center, can provide an adjustment to the particle orbit to remove the term driving the change in spin tune. For horizontal displacements, the MXS family of four magnets is the best choice since they are located at the beginning of the arcs where the horizontal beam size is large.

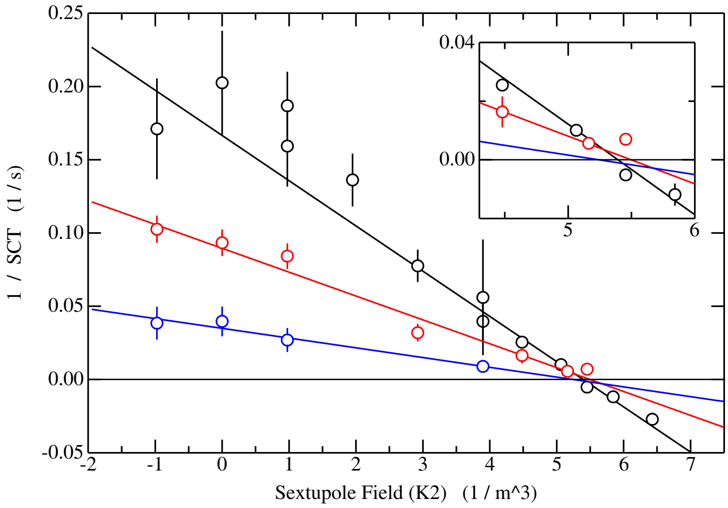


Fig. 6. – Measurements of the reciprocal of spin coherence time. The horizontal scale is the sextupole magnetic field strength. The three lines correspond to three different beam profile widths, starting from a narrow (bottom, blue) to a wide (top, black) profile. In order to determine wether this behavior is linear, all the points above the zero crossing at $5.4 \pm 0.1\,\mathrm{m}^{-3}$ were reversed in sign.

Using a setup with one of the larger horizontal beam profiles, the horizontal polarization lifetime was measured as a function of the setting of the MXS magnet strength. An initial investigation showed that changes were capable of lengthening the polarization lifetime. In contrast to the data shown in fig. 5, the measure of the lifetime is changed to the spin coherence time explained in sect. **3**. The results are shown in fig. 6 which plots the reciprocal of the spin coherence time ($1/a_2$ scaled to 1/seconds) as a function of the strength of the MXS sextupole magnets. If the magnet strength increases beyond the point where the 1/SCT becomes zero and the spin tune spread is canceled, then a finite polarization lifetime will return. In order to determine whether this behavior is linear, it is necessary that the 1/SCT values on one side or the other of such a zero crossing be reversed in sign. In fig. 6, this was done to all of the points above $5.4 \pm 0.1\,\mathrm{m}^{-3}$

Changing the value of the sextupole field has a dramatic effect on the horizontal polarization lifetime. This approaches infinity as the 1/SCT goes to zero. The linearity of the effect comes from the matching of the quadratic sextupole field as a correction to the quadratic path lengthening, a function of the size of the horizontal emittance. Over most of this range, the dependence is clearly linear (after correction of the sign). The lack of distortions in the linear behavior near value of zero points to the lack of other contributions to shortening the polarization lifetime. Such contributions could come from the vertical beam emittance or couplings to the momentum spread.

Another test was made to measure the horizontal polarization lifetimes by cooling the beam for all the storage time, since it represents the case where the particle momentum distribution and emittances are the smallest. The beam was extracted onto the EDDA thick carbon target for only a short time at the beginning and end of the horizontal polarization window. Under these conditions, the longest polarization lifetime recorded is $316 \pm 40\,\mathrm{s}$ for the time required for the polarization to fall to $1/e$ of its initial value.

6. – Conclusions and outlook

The goal of this set of experiments was to provide a demonstration that sextupole fields in a storage ring may be used to reduced the spread of spin tunes in a horizontally polarized deuteron beam. Such a demonstration is a critical part of showing that it is possible to build a special storage ring dedicated to the search for an Electric Dipole Moment (EDM) on charged particles. In order to have a sensitivity to the deuteron EDM that is about 10^{-29} e·cm, the spin coherence time should reach 1000 s.

The spin coherence time studies presented here confirm that the proper choice of sextupole fields could be used to preserve the polarization for times up to 1000 s. The correction illustrated in fig. 6 is for the one-dimensional problem, fixing a large horizontal emittance and spin tune spread with a sextupole located at a place with a large horizontal beta function. The zero crossing point represents the condition in which the spin tune spread due to the horizontal emittance is cancelled and it happens for a sextupole field strength of $5.4 \pm 0.1\,\mathrm{m}^{-3}$. In general, both X and Y emittance must be corrected. The MXL sextupole family is located where the vertical beta function is large, and is thus the right choice for the Y dimension. It is expected that the cancellation will require a consideration of the cross terms, MXS changing Y and MXL changing X. This study is left for the future.

It is also demonstrated that a long horizontal polarization lifetime (316 ± 40 s) can be achieved in the case of a cooled beam, since it represents the case where the particle momentum distribution and emittances are the smallest. Although this result is promising as it approaches the goal value for dedicated EDM measurements, the adopted cooling technique, making use of the electron cooler, cannot be directly applied to the final experiment as the magnetic fields used in the electron cooling system would destroy the EDM signal. As a possible alternative, the use of stochastic cooling has been proposed, but the effect of the stochastic cooling system on the spin dynamics of the stored beam has to be both theoretically and experimentally investigated.

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