

SPIN COHERENCE TIME LENGTHENING FOR A POLARIZED DEUTERON BEAM USING SEXTUPOLE FIELDS

G. Guidoboni, University of Ferrara and INFN, Ferrara, Italy

Abstract

The possibility to use sextupole fields to increase the in-plane (ring plane) polarization lifetime of a deuteron beam is part of the feasibility studies for a search for an electric dipole moment (EDM) of charged particles in storage rings. This experiment requires ring conditions that can ensure a lifetime of the in-plane polarization (spin coherence time, SCT) up to 1000 s. At the COoler SYnchrotron (COSY) located at the Forschungszentrum Jülich, the JEDI collaboration has begun to examine the effects of emittance and momentum spread on the SCT of a polarized deuteron beam at 0.97 GeV/c. The set of data presented here shows how second-order effects from emittance and momentum spread of the beam affect the lifetime of the horizontal polarization of a bunched beam. It has been observed that sextupole fields can correct for depolarizing sources and increase the spin coherence time up to hundreds of seconds while setting the chromaticities equal to zero.

INTRODUCTION

The spin coherence time (SCT) measurements presented here are part of feasibility studies [1, 2] for a new project searching for the electric dipole moment (EDM) of charged particles in storage rings. The EDM is a permanent charge separation within the particle volume, aligned along the spin axis. The EDM violates both parity conservation and time reversal invariance. Thus, assuming the validity of the CPT theorem, the EDM represents a source of CP violation that could explain why the universe evolved to a matter-dominated state. The Standard Model (SM) does not explain the observed baryon asymmetry and predicts unobservably small EDMs (*e.g.*, for the proton, $|d_p|_{\text{SM}} < 10^{-32}$ e·cm). Models beyond the SM predict values within the sensitivity of current or planned experiments (for proton and deuteron $|d_{p,d}| \geq 10^{-29}$ e·cm), but no EDM has been observed yet. If an EDM is found within the present experimental limits it would be a clear and clean probe of new physics.

Since the EDM lies along the spin axis, the new detection method requires observing the polarization precession in an electric field while the charged particles are trapped in a storage ring. While keeping the horizontal component of the beam polarization along the velocity direction during the storage time, the EDM signal can be detected as a rotation of the polarization from the ring plane toward the vertical direction due to the interaction with the inward radial electric field that is always present in the particle frame. In a magnetic storage ring, the polarization will undergo a rotation relative to the velocity described by the Thomas-

BMT equation [3]:

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

where it is assumed that $\vec{\beta} \cdot \vec{B} = \vec{\beta} \cdot \vec{E} = 0$ and the EDM component has been omitted. $\vec{\omega}_s$ is the spin precession in the horizontal (ring) plane, $\vec{\omega}_c$ is the particle angular frequency and $G = \frac{g-2}{2}$ is the anomalous magnetic moment. In the deuteron case, where $G = -0.14$, the spin alignment along the velocity ($\vec{\omega}_a = 0$ in Eq. 1) is achieved with a combination of magnetic and outward electric fields. In order to reach a sensitivity of 10^{-29} e·cm, a good compromise for the experiment requires a polarimeter sensitivity of 10^{-6} rad and a horizontal polarization lifetime (SCT) of 1000 s. The SCT represents the time available to observe the EDM signal as a polarization precession toward the vertical direction. The aim of the feasibility studies made at COSY (COoler SYnchrotron at the Forschungszentrum Jülich, Germany) is to demonstrate the possibility to reach an SCT of 1000 s using sextupole field corrections and a dedicated beam preparation including beam bunching and electron cooling.

EXPERIMENTAL SETUP

The EDM feasibility studies started at COSY in 2012 using a polarized deuteron beam with a momentum of 0.97 GeV/c. The beam polarization was initially aligned along the vertical direction (orthogonal to the ring plane) and then rotated to the horizontal (ring) plane by exciting the $(1 - G\gamma)$ spin resonance with an RF-solenoid, where G is the anomalous magnetic moment and γ is the relativistic factor. With the development of a DAQ (Data Acquisition system) capable of measuring the rapidly precessing polarization (≈ 120 kHz) in the ring plane [4], it was possible to continuously measure the horizontal polarization as a function of time by slowly extracting the beam onto a thick carbon target and observing elastic scattering events at forward angles in the EDDA detector [5]. The beam was bunched at the first harmonic in order to remove the first order momentum spread ($\Delta p/p$) as a cause of the in-plane spin decoherence.

The SCT studies aimed to investigate the decoherence sources represented by the finite transverse beam size (emittance) and the second order momentum spread of the beam, $((\Delta p/p)^2)$, arising from synchrotron oscillations. With the combination of electron cooling, bunching and white noise applied to electric field plates, it was possible to prepare different beam setups to separately study the single contributions. The sequence of doing electron cooling first, then bunching without cooling, was used to study the effect of $(\Delta p/p)^2$ alone. In another setup, electron cooling and

bunching together reduced the contribution from $(\Delta p/p)^2$ and created the conditions to study emittance effects. White noise was applied for few seconds in order to increase the horizontal transverse beam size after the electron cooling was turned off. It was not possible to study the contribution from vertical emittance due to machine acceptance limitations.

The horizontal polarization lifetime of the beam was manipulated using three sextupole families in the COSY arcs. In particular, the families used were MXG, MXL and MXS because of their favourable positions in the ring where, respectively, the dispersion function D and the beta functions β_y and β_x are the largest.

SEXTUPOLE CORRECTIONS ON EMITTANCE

Spin tracking calculations [6] suggested that the empirical dependence of the inverse of the SCT on the sextupole fields is given by:

$$\begin{aligned} \frac{1}{SCT} = & |A + a_1 S + a_2 L + a_3 G| \theta_x^2 + \\ & |B + b_1 S + b_2 L + b_3 G| \theta_y^2 + \\ & |C + c_1 S + c_2 L + c_3 G| (\Delta p/p)^2 \end{aligned} \quad (2)$$

where S , L and G represent the field strengths of the sextupoles in COSY (MXS, MXL and MXG respectively), θ_x^2 , θ_y^2 and $(\Delta p/p)^2$ are the horizontal and vertical beam widths and second order momentum spread. The coefficients from A to c_3 describe the linear dependence of $1/SCT$ on ring properties and sextupole strengths.

An initial SCT investigation in 2012 showed that changes to the MXS sextupole strength were capable of lengthening the polarization lifetime [1] of a horizontally wide beam (that means a large contribution from θ_x^2 and negligible contributions from θ_y^2 and $(\Delta p/p)^2$), reproducing the linear behavior predicted by Eq. (2).

The results are shown in Fig. 1 which plots the reciprocal of the SCT as a function of the strength of the MXS sextupole magnets. For this particular set of data, the SCT was defined as the gaussian width of the horizontal polarization curve, as described in [4]. The horizontal beam size was enlarged in order to study the decoherence effect due to horizontal emittance (θ_x^2), while the other two sextupole families were set to zero and the contributions from θ_y^2 and $(\Delta p/p)^2$ were negligible. The sets of data corresponding to two beam profile widths are shown in Fig. 1 and identified by black (beam width of 7.4 mm) and red (beam width of 4.6 mm) lines. The beam profile width has been measured as the Gaussian width of the beam.

As a function of the sextupole current (S in Eq. 2), the values of $1/SCT$ should fall along the absolute value of a straight line. To show the linear dependence more clearly, the absolute value for the curves in Fig. 1 has been removed and the signs of the measurements above 5.4 m^{-3} have been changed for the black data with the largest heating. As

$1/SCT$ gets small, it is possible for more than one term in Eq. 2 to contribute; some points near zero were excluded from the linear fits shown in Fig. 1.

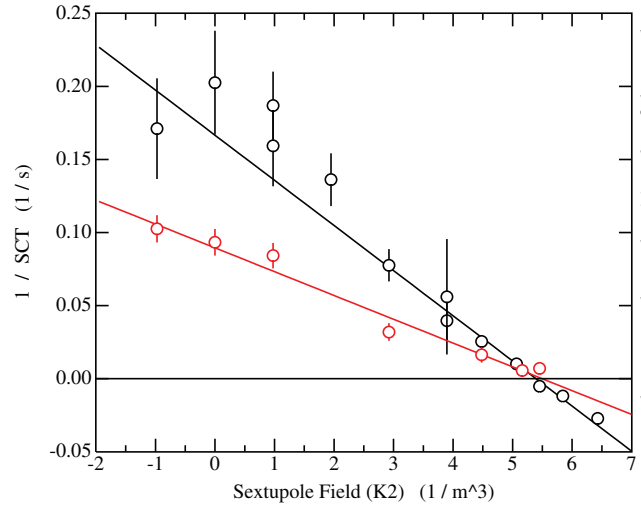


Figure 1: Measurements of the reciprocal of spin coherence time as a function of the MXS sextupole magnetic field strength, K2. The two lines correspond to two different horizontal beam profile widths, a narrow (red, beam width of 4.6 mm) and a wide (black, beam width of 7.4 mm) profile. In order to determine whether this behavior is linear, as expected from Eq. 2, all the black points above the zero crossing at $5.4 \pm 0.1 \text{ m}^{-3}$ were reversed in sign.

CHROMATICITY EFFECT

During the last beam time in 2014 the SCT measurements included the beam setup for a large $(\Delta p/p)^2$ and a scan over the three sextupole families (MXG, MXL and MXS) to study the relationship between chromaticity and SCT.

Figure 2 shows the two chromaticity planes (vertical Y and horizontal X) mapped as functions of MXS and MXG, while keeping MXL at -0.2 m^{-3} . This specific value for MXL was chosen to make the chromaticity zero lines (dashed lines) close to each other. An example of a horizontal polarization measurement is shown in Fig. 3, where the SCT was defined as modulus of the constant p_0 over the slope p_1 from the linear fit applied to the horizontal polarization curve. The location of the longest SCTs from scans in sextupole space are shown in Fig. 4 together with the chromaticity zero lines. On the \hat{x} and \hat{y} axes are the values of the field strengths for MXS and MXG with MXL $= -0.2 \text{ m}^{-3}$. The red circles represent the best SCTs for the horizontally wide beam and the black dots the best SCTs for the large $(\Delta p/p)^2$ contribution. In both cases, the error bars are less than the size of the symbols. The green and blue lines are respectively the horizontal and vertical chromaticity zero lines with an error of about 1%. The result is that the longest polarization lifetimes are found near chromaticity zero, suggesting that both horizontal width and longitudinal spread decoherence sources are cancelled at a place where both chromaticities (X and Y) are zero.

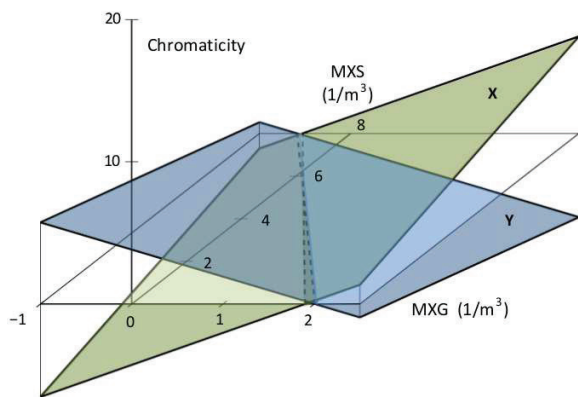


Figure 2: X and Y chromaticities measurements as a function of the sextupole fields MXS and MXG with $MXL = -0.2 \text{ m}^{-3}$. The dashed lines represent the loci where chromaticities are zero.

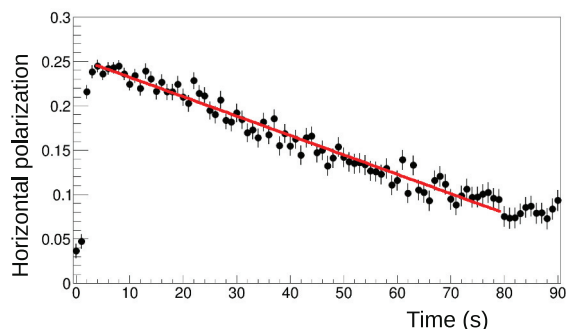


Figure 3: An example of a horizontal polarization measurement with a linear fit shown by a red line. The slope is proportional to the inverse of SCT in a first approximation.

CONCLUSIONS

Figure 5 is an example of preliminary analysis that shows a scan over MXG with $MXS = 2 \text{ m}^{-3}$ for the case of a large $(\Delta p/p)^2$. The longest SCT is above 1000 s. From all the measurements acquired in August 2014, it is possible to conclude that the SCT of a horizontally polarized deuteron beam with $p = 0.97 \text{ GeV/c}$ may be substantially extended (up to 1000 s) through a combination of sextupole fields that set both the X and Y chromaticities to zero in addition to a dedicated beam preparation with bunching and electron cooling. This meets the requirements for a storage ring to search for an EDM.

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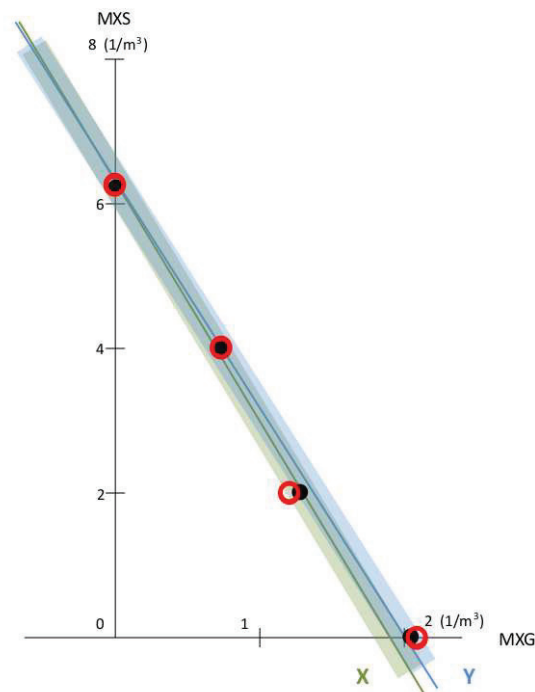


Figure 4: The preliminary result of SCT measurements for two set of data. The longest horizontal polarization life times (red circles for horizontally wide beam, black dots for large $(\Delta p/p)^2$) lie along the zero chromaticity lines (green is the horizontal and blue is the vertical chromaticity).

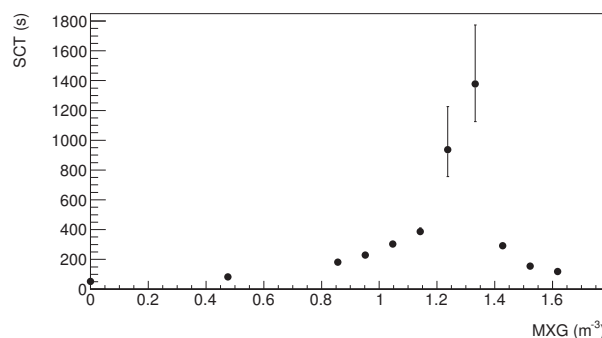


Figure 5: A preliminary result showing the SCT defined as $-p_0/p_1$ from the linear fit of the horizontal polarization as function of MXG. This particular example was recorded in the case of large $\Delta p/p$ with $MXS = 2 \text{ m}^{-3}$ and $MXL = -0.2 \text{ m}^{-3}$. The longest SCT that was measured appears at $MXG = 1.33 \text{ m}^{-3}$ and it is above 1000 s.

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