Spin coherence time studies of a horizontally polarized deuteron beam at COSY

G Guidoboni on behalf of the JEDI Collaboration‡

Ferrara University and INFN, 44122 Ferrara, IT

E-mail: guidoboni@fe.infn.it

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Abstract. The measurement of a non-zero electric dipole moment (EDM) aligned along the spin of sub-atomic particles would probe new physics beyond the standard model. It has been proposed to search for the EDM of charged particles using a storage ring and a longitudinally polarized beam. The EDM signal would be a rotation of the polarization from the horizontal plane toward 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 lifetime of the in-plane polarization (spin coherence time, SCT) up to 1000 s. A study has begun 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 a direct measurement of a rapidly rotating horizontal polarization as a function of time. 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 demonstrated that sextupole fields can be used to correct for these depolarizing sources and increase the spin coherence time up to hundreds of seconds.

1. Introduction

The Spin Coherence Time (SCT) measurements presented in this paper are part of feasibility studies [1, 2] of 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 which 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, $|d_p|_{\mathrm{SM}} < 10^{-32}\, e{\cdot}\mathrm{cm}$). Models beyond the SM predict values within the sensitivity of current or planned experiments (for proton and deuteron

‡ http://collaborations.fz-juelich.de/ikp/jedi/collaboration/members.shtml

$|d_{p,d}| \geq 10^{-29}$ 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]:

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

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 of 1000 s, called the *spin coherence time*. The SCT represents the time available to observe the EDM signal as a polarization precession toward the vertical direction. The aim of this paper is to describe the feasibility studies made at COSY (COoler SYnchrotron at the Forschungszentrum Jülich, Germany) to demonstrate the possibility to reach a SCT of 1000 s using sextupole field corrections and a dedicated beam preparation including beam bunching and electron cooling.

2. Experimental setup at COSY

The SCT studies at COSY 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.

In order to separately study these two contributions, a polarized deuteron beam with a momentum $p = 0.97$ GeV/c has been manipulated with the electron cooler to minimize the beam size and bunched, so that the first order $\Delta p/p$ contributions on average vanish. A beam setup with a large $(\Delta p/p)^2$ associated with synchrotron oscillations was obtained by first cooling the beam for 60 s and then bunching it at the first harmonic after the cooling was off. The second setup with large horizontal emittance contributions was created by cooling and bunching the beam at the same time for 60 s (to reduce the momentum spread), then turning cooling off and switching horizontal heating on (white noise applied to horizontal electric field plates) for 5 s. In each case, the polarization was then rotated from the vertical direction into the ring plane using an RF solenoid.

The beam polarization was continuously measured by applying white noise to vertical electric field plates in order to extract the beam onto a 17 mm thick carbon target. Elastically scattered deuterons were detected in the EDDA polarimeter since elastic scattering is a spin sensitive process and the cross section for d+C scattering is large [4]. The EDDA scintillators were grouped in 4 sectors (up, right, down and left) used to calculate the Left-Right asymmetry (proportional to vertical polarization) and the Up-Down asymmetry (proportional to the horizontal polarization). A dedicated DAQ was developed in 2012 in order to measure the rapidly precessing polarization in the horizontal plane [5].

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 (see Fig. 1). MXG is located where the dispersion function D is the largest, so particles with large $\Delta p/p$ travel through shorter or longer path respect to the reference orbit. MXL and MXS are respectively located where the beta functions β_y and β_x are the largest, so the vertical and horizontal beam sizes are the widest along the ring.

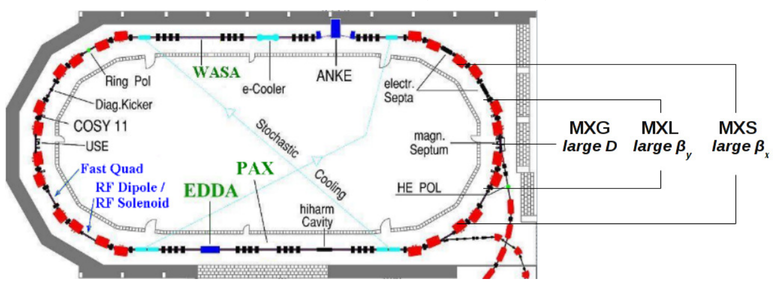

Figure 1: Structure of the COSY ring where the position of the sextupoles magnets is indicated on the right arc. The same sextupole arrangment is valid for the left arc.

3. Sextupole effect on SCT

Spin tracking calculation [6] suggest that the empirical dependence of the inverse of the SCT versus 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 strength of the sextupoles in COSY (MXS, MXL and MXG respectively) and θ_x^2, θ_y^2 and $(\Delta p/p)^2$ are the horizontal and vertical beam width and second order momentum spread. The coefficients from A to c_3 describe the linear dependence of $1/SCT$ on sextupole strengths (absolute values keep 1/SCT positive). In the next section the SCT measurements will be presented for the cases of a horizontally wide beam and a large second order momentum spread.

4. SCT measurements

An initial SCT investigation from 2012 showed that changes to the MXS sextupole strength were capable of lengthening the polarization lifetime. The results are shown in Fig. 2 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 [5]. The horizontal beam size

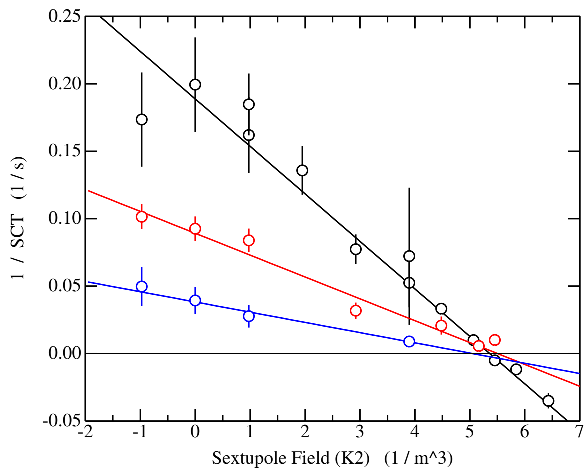

Figure 2: Measurements of the reciprocal of spin coherence time as a function of the MXS sextupole magnetic field strength. The three lines correspond to three different horizontal beam profile widths, starting from a narrow (bottom, blue) to a wide (top, black) profile. In order to determine whether this behavior is linear as expected from Eq. 2, all the black points above the zero crossing at 5.4 ± 0.1 m^{-3} were reversed in sign.

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 three beam profile widths are shown in Fig. 2 and identified by black (wide horizontal profile), red (medium) and blue (narrow) lines.

If the magnet strength, K2, increases beyond the point where 1/SCT becomes zero and the spin tune spread is canceled, then a finite polarization lifetime will return. In order to illustrate that this behavior remains linear, one can flip sign of the 1/SCT values above 5.4 m^{-3} as has been done for the black points. At small values of 1/SCT, other terms in Eq. (2) may contribute, keeping the lifetime from becoming infinite. So some points near 5.4 m^{-3} were excluded from the straight line fits to remove any possible distortions.

In 2014 the SCT measurements were extended to include the beam setup which provides a large contribution from $(\Delta p/p)^2$ and to involve a scan over the three sextupole families, MXG, MXL and MXS. The case with large vertical emittance was never studied due to a limited machine acceptance. Fig. 3 shows the preliminary results from the last beam time in August 2014. On the top left side there are the two chromaticity planes (vertical Y and horizontal X) mapped for several values of MXS and MXG, while keeping MXL at −1.45% of the full power scale. This specific value for MXL was chosen because the chromaticity zero lines (dashed lines) are close to each other. An example of a horizontal polarization measurement is drawn in the bottom left corner of Fig. 3. In the online analysis, the SCT was defined to be the zero intercept p_0 over the slope p_1 from the linear fit (red line) applied to the horizontal polarization curve.

The location in sextupole space of the longest SCTs are shown on the right side of

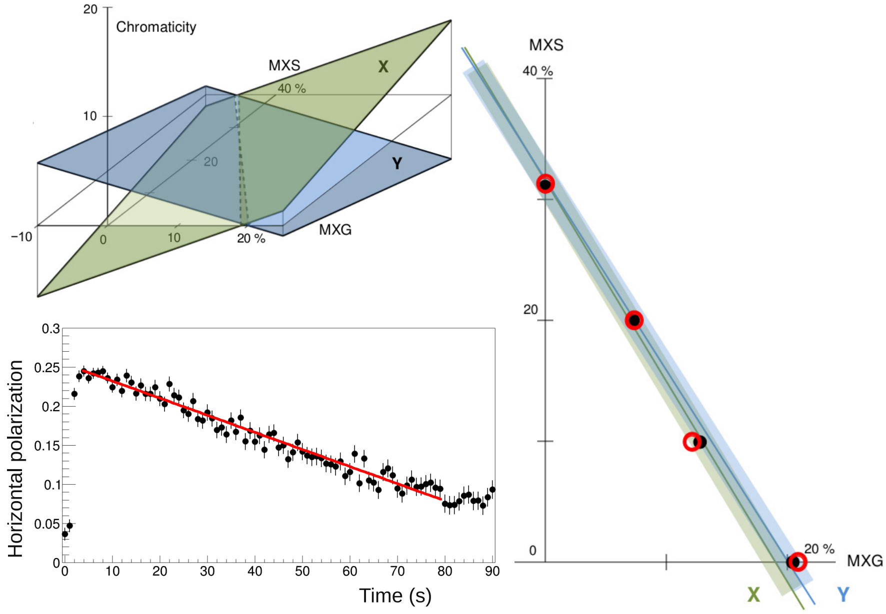

Figure 3: Top-left: X and Y chromaticities measurements as a function of the sextupole fields MXS and MXG with MXL=−1.45%. The scales are in percent of the power supply full range. The dashed lines represent the loci where chromaticities are zero. Bottom-left: an example of horizontal polarization measurement with a linear fit shown with a red line. The slope is proportional to the inverse of SCT in a first approximation. Right side: 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).

Fig. 3 together with the chromaticity zero lines. On the $\hat{x}$ and $\hat{y}$ axis there are the values in percent of the full power scale for MXS and MXG, and MXL=−1.45%. 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 the middle of the range for chromaticity zero, suggesting that it is best to have MXS and MXG nearly equal. This means that both horizontal width and longitudinal spread decoherence sources are cancelled at a places where both chromaticities (X and Y) are zero.

5. Conclusions

The observation of a non-zero EDM would be a clear probe of new physics. A new experimental method has been proposed for an EDM measurement on charged particles, based on the use of storage rings and polarized beams, with a requirement of 1000 s for the SCT. It has been demonstrated that the lifetime of a horizontally polarized

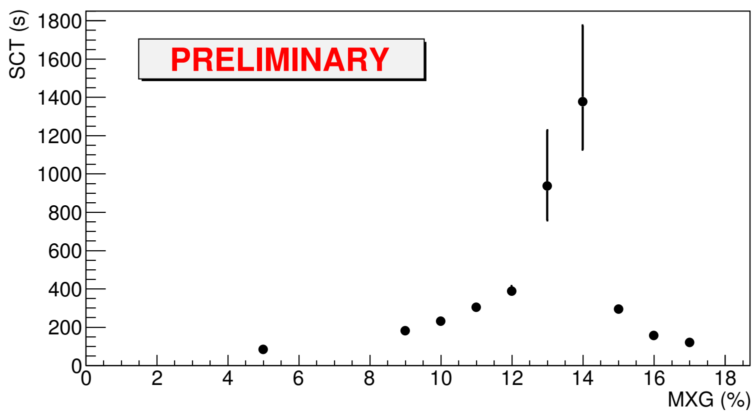

Figure 4: A preliminary result showing the SCT defined as $-p_0/p_1$ from the linear fit of the horizontal polarization as function of MXG, expressed as a % of the full power scale. This particular example was recorded in the case of large $(\Delta p/p)^2$ with MXS=10% and MXL=−1.45%. The longest SCT that was measured appears at MXG=14% and it is above 1000 s within the error range.

deuteron beam may be substantially extended (up to ∼ 1000 s, see Fig. 4) through a combination of sextupole fields that make both the X and Y chromaticities zero, in addition to a dedicated beam preparation with bunching and electron cooling.

This meets the requirement for a storage ring to search for an EDM.

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